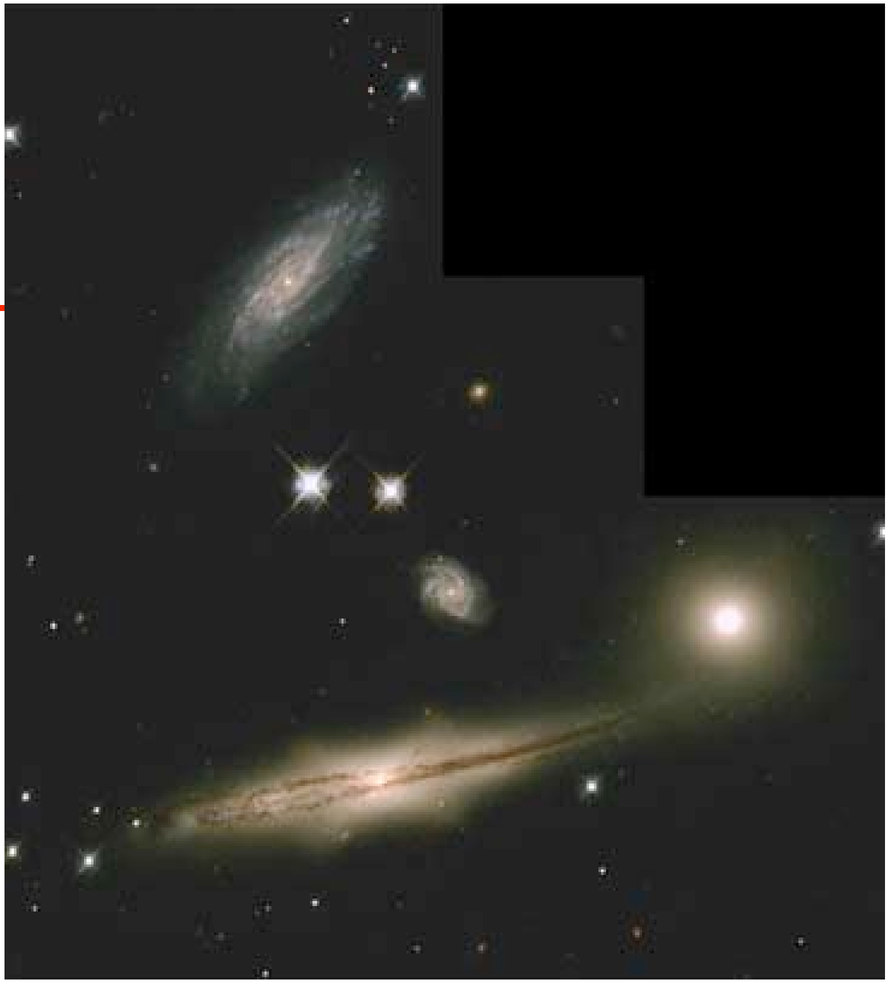
Extragalactic Globular Clusters & Galaxy Assembly



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Study of Astrophysics of Globular clusters in Extragalactic Systems

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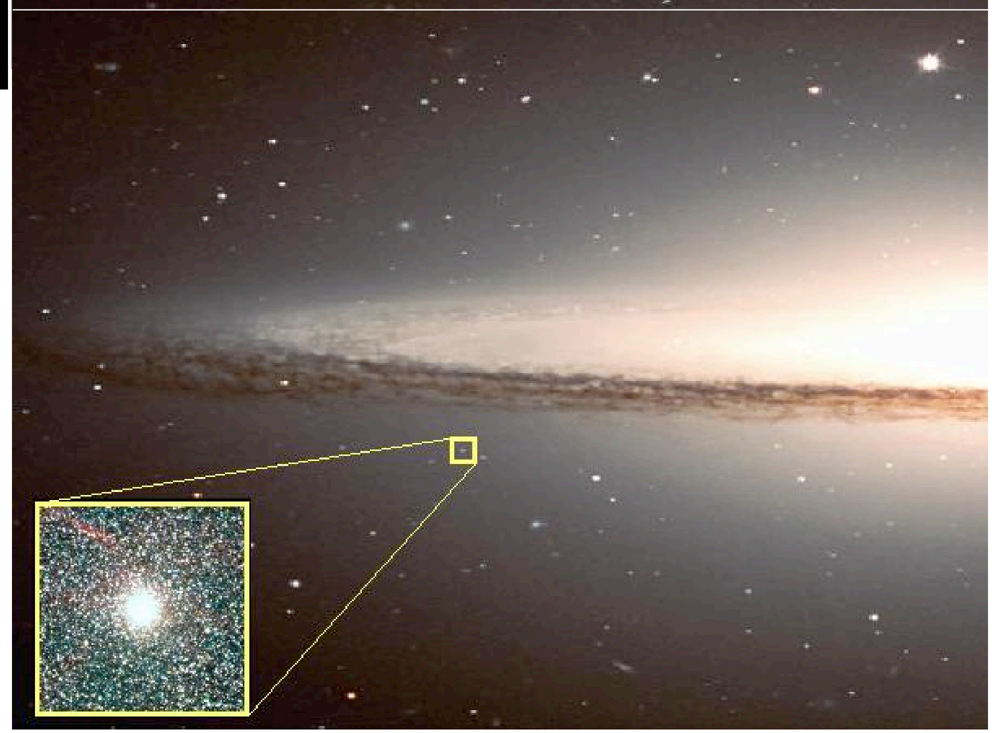
Overview

- Background
  - Relevant characteristics of GC systems
- Globular Cluster/Galaxy Formation
  - Sub-populations
  - Early and late-type galaxies
  - Formation Scenarios
- SAGES programs
  - Recent results from HST and Keck
- Summary and implications

Globular Cluster Properties

- SSPs – single age and metallicity
- $10^5 - 10^6\ M_{sun}$
- All galaxies $M_V < -15$ have at least one GC
- ~150 in MW
  ~400 in M31
  > 10,000 in some ellipticals
- $S_N \equiv N_{GC} \times 10^{0.4(M_V+15)}$
  2 – 3 × greater in E's

M 13



- Oldest radiant objects in universe
- Associated with galaxies of all morphological types
- Constrain theories of galaxy formation

    When and how?

    Differences

Good tracers of star formation histories of galaxies

- Massive star clusters form during all major star formation events (Schweizer 2001)
- #of young clusters scales with amount of gas involved in interaction (Kissler-Patig et al 1998)
- Cluster formation efficiency depends on SFR in spirals (Larsen & Richtler 2000)
- Advantages over galaxy starlight
  — difficult to disentangle different stellar populations
  — recent but unimportant (in mass) star formation episode can dominate

NGC 6946 Larsen et al 2001

Advantages over galaxy starlight

- GCs are simple stellar populations
  — single age and metallicity
- GCs can be studied out to several R_{eff}
  — probe DM halos/galaxy cluster potential
- Galaxy starlight usually only sampled in center $\leq 1\ R_{eff}$
  — difficult to disentangle different stellar populations
  — recent but unimportant (in mass) star formation episode can dominate

Multiple Populations

If all major star formation is accompanied by GC formation

then

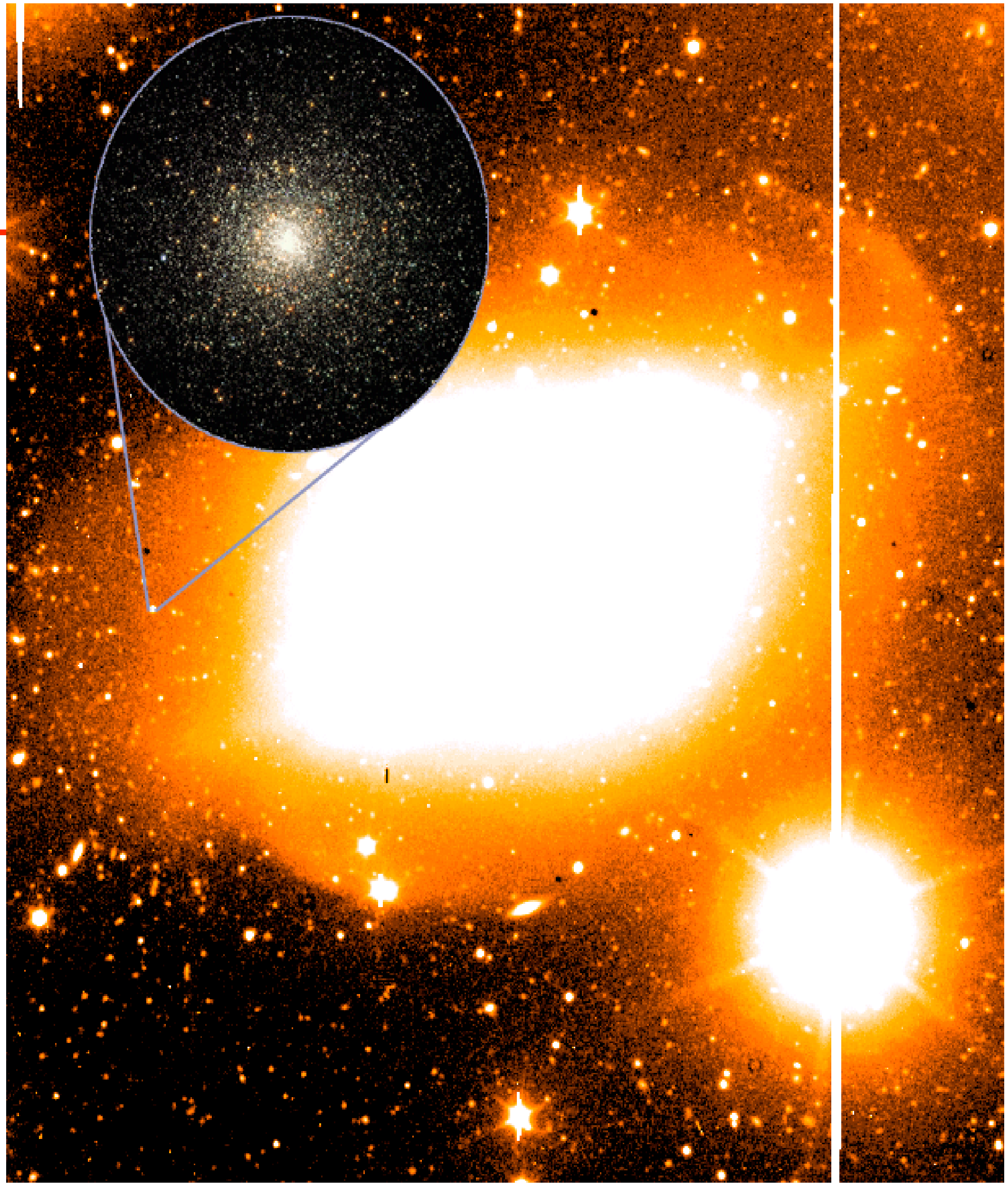
More than one GC population should be observable in a galaxy that underwent more than one major star formation event

and

Relative numbers indicate relative importance of episodes at their origin

Challenges

- Faint
- Superimposed on background light of parent galaxy
- Contamination – difficult to distinguish from foreground stars and background galaxies (from ground)



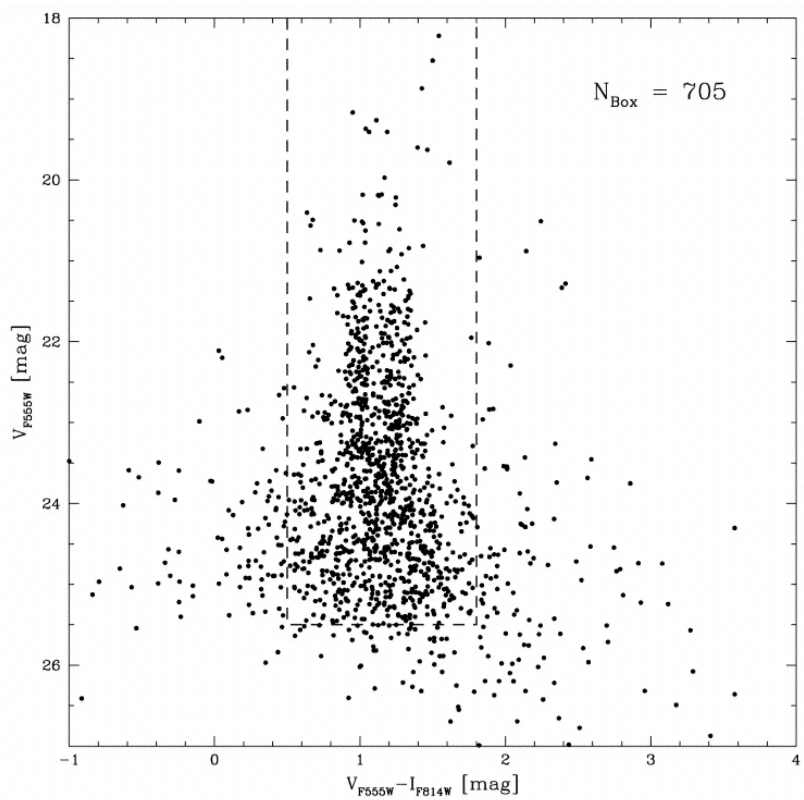
Telescopes

Bimodal Color Distributions

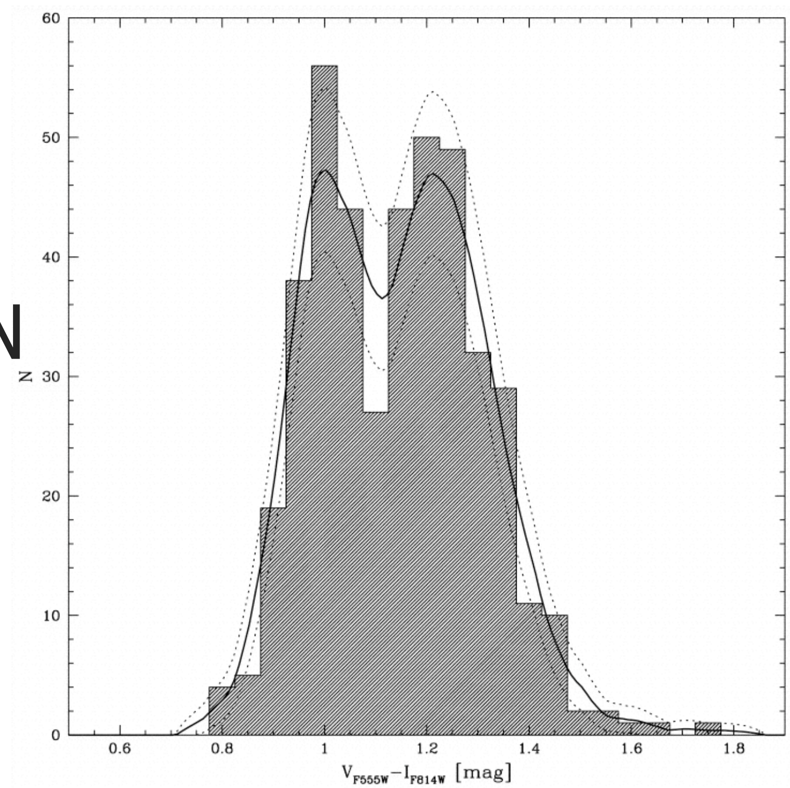
NGC 4472 (M49)

Puzia et al. (1999) AJ

V



N



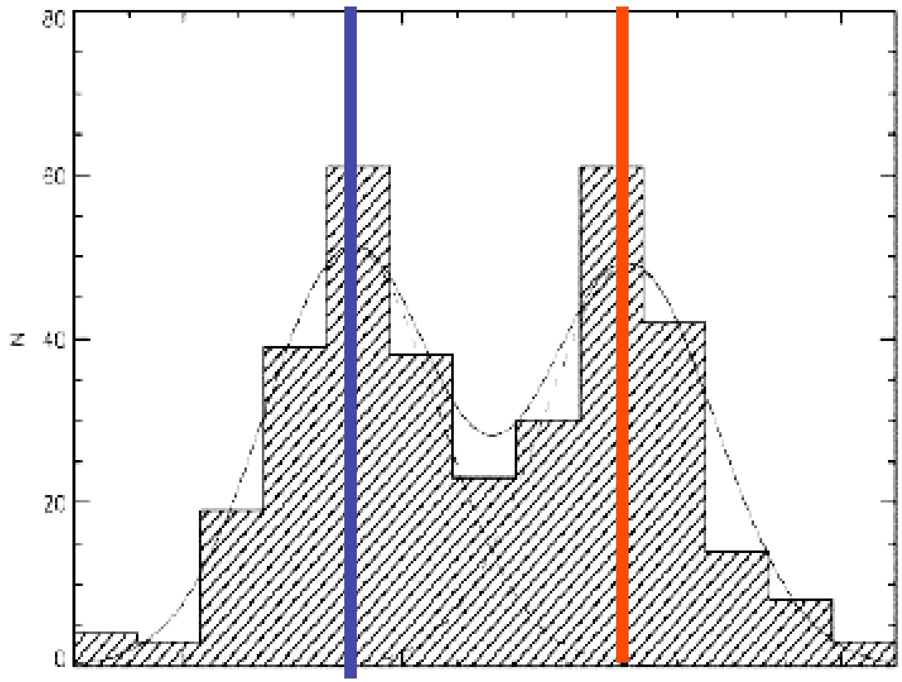
V-I

Implications

Bimodal color distributions ⇒
globular cluster sub-populations

Color differences are due to
age differences
and /or
metallicity differences

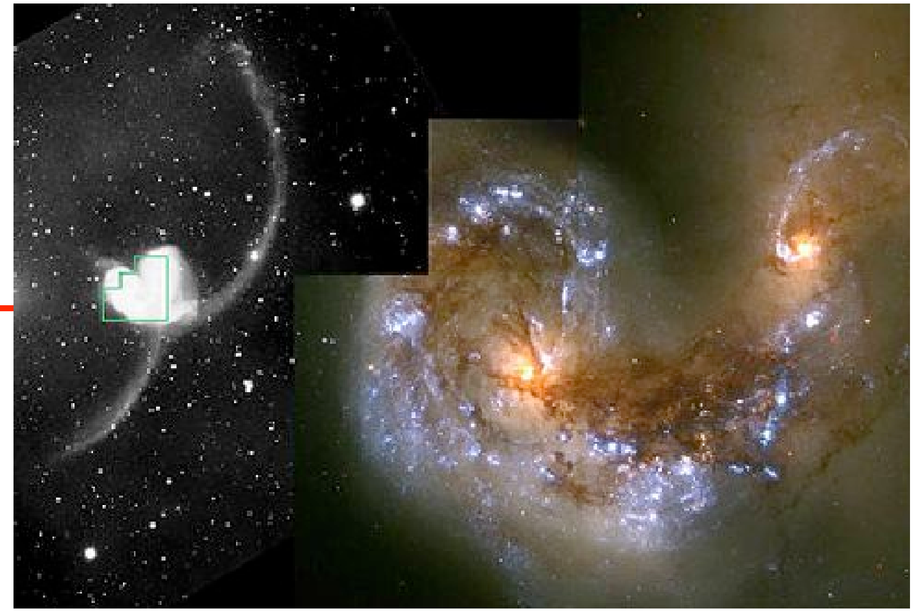
⇒ Multiple epochs and/or mechanisms of formation



[Fe/H] = -1.55 -0.55

V-I = 0.95 1.15

GC/Galaxy Formation Models

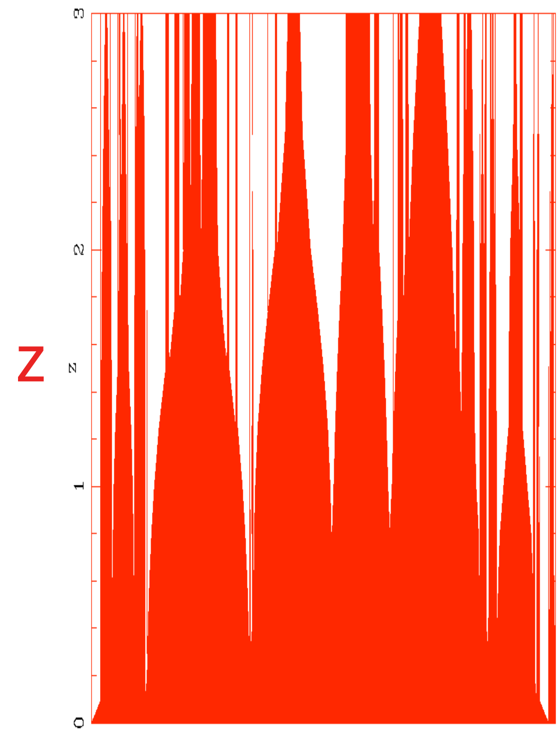


1. Formation of ellipticals/GCs in mergers (Schweizer 1987, Ashman & Zepf 1992)

2. In situ/multi-phase collapse (Forbes, Brodie & Grillmair 1997)

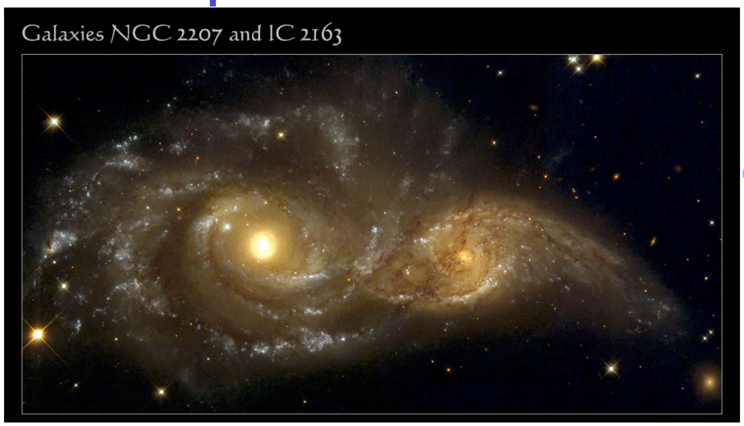
3. Accretion/stripping (Cote' et al. 1998)

4. Hierarchical merging (Beasley et al. 2002)

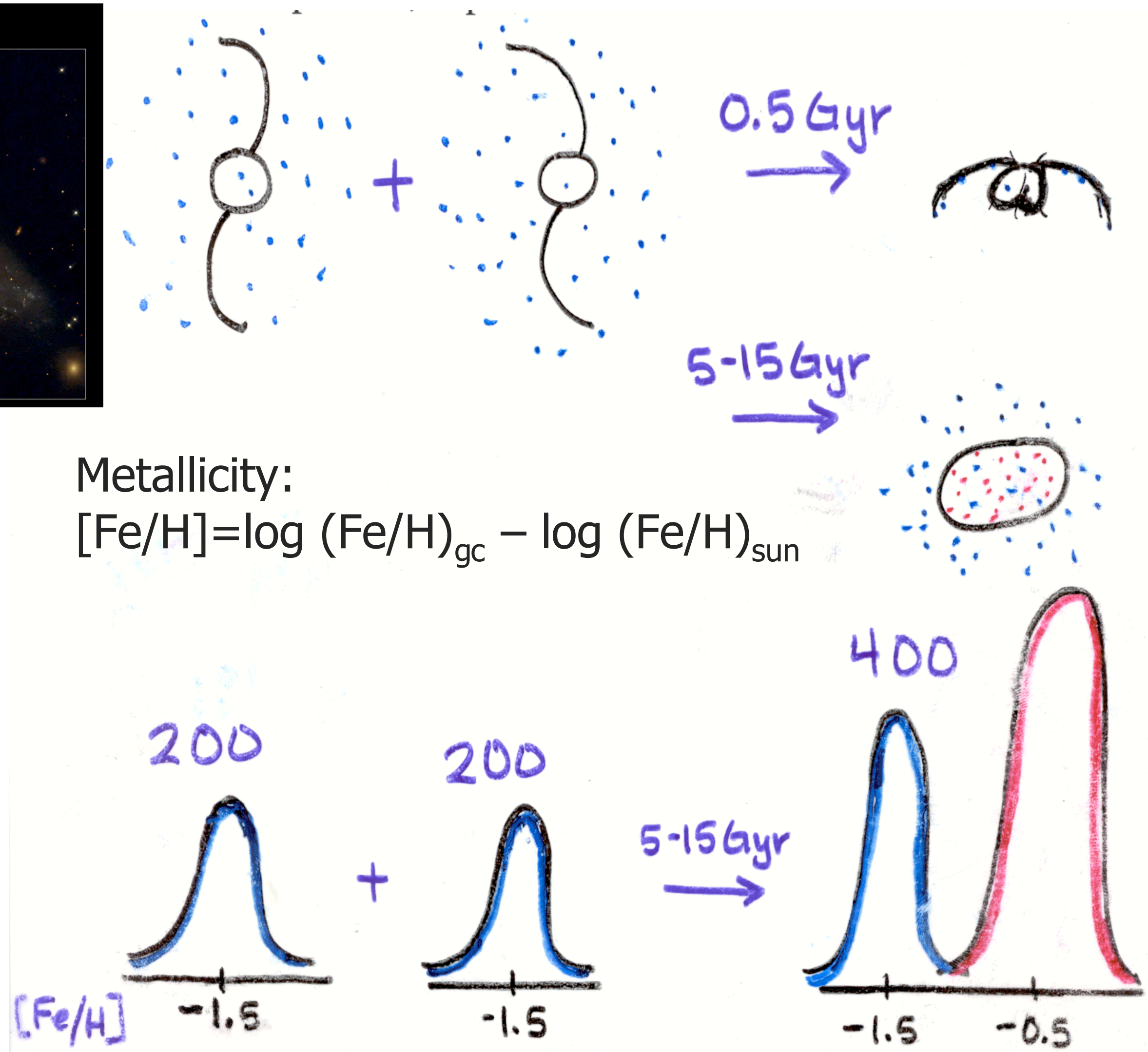


2 & 4 require (temporary) truncation of GC formation at high redshift

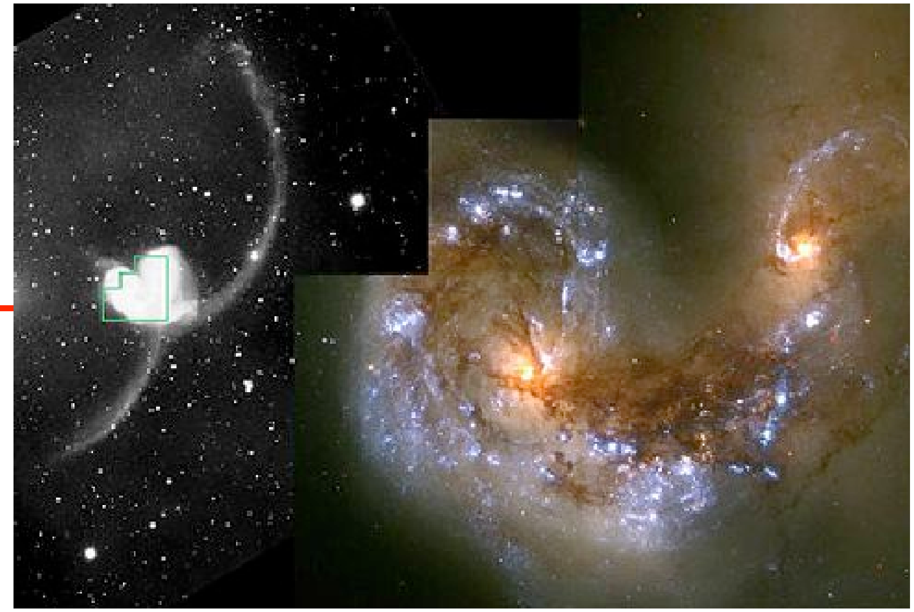
New Globular Clusters in Mergers



- S_N problem (van den Bergh 1984)
- Globular clusters form in mergers (Schweizer 1987, Ashman & Zepf 92)



GC/Galaxy Formation Models



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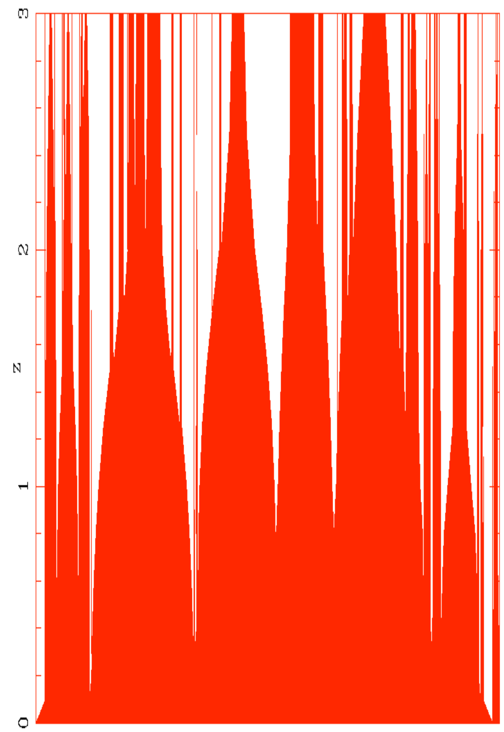


2 & 4 require (temporary) truncation of GC formation at high redshift

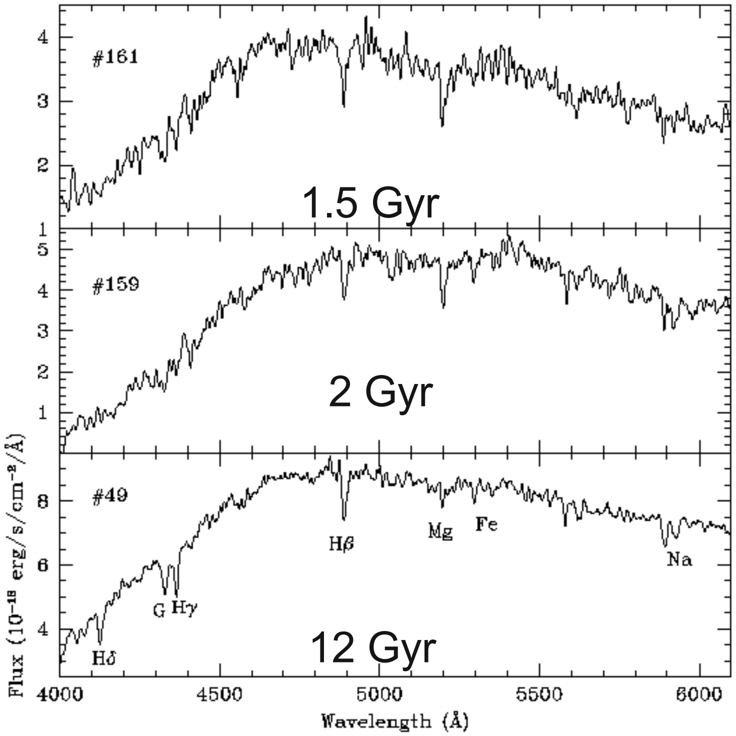
Model Predictions

Key properties:

Ages, metallicities, abundance ratios, kinematics, luminosity functions of red and blue sub-pops

- Merger model → old population (~age of universe less ~1 Gyr) +young population with age of merger
- Multi-phase collapse → 2 old populations one slightly (~2–4 Gyr) younger than other
- Accretion → blue and red clusters about the same age
- Hierarchical merging → age substructure in red sub-pop + red globulars in low-luminosity field/group ellipticals ~ 2 Gyr younger than in bright cluster ellipticals

How well can we estimate ages?



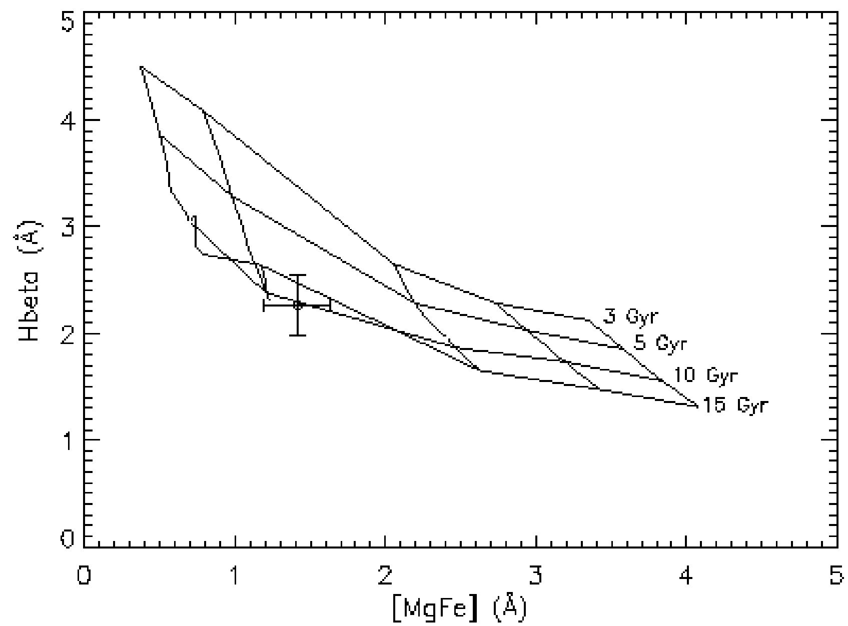
At distance of Virgo 6 hrs with Keck

⇒ H_β errors: +/- 0.15 – 0.3 Å

⇒ 2 – 4 Gyr at 12 Gyr

Model-dependent absolute ages

Relative ages ~OK



- Models are highly degenerate at low metallicities and old ages
- Cannot distinguish relative ages > 10 Gyr in low metallicty ([Fe/H]≤– 1) systems
- Caveats BHBs, AGB luminosity function

GC Ages

SAGES Keck spectroscopy

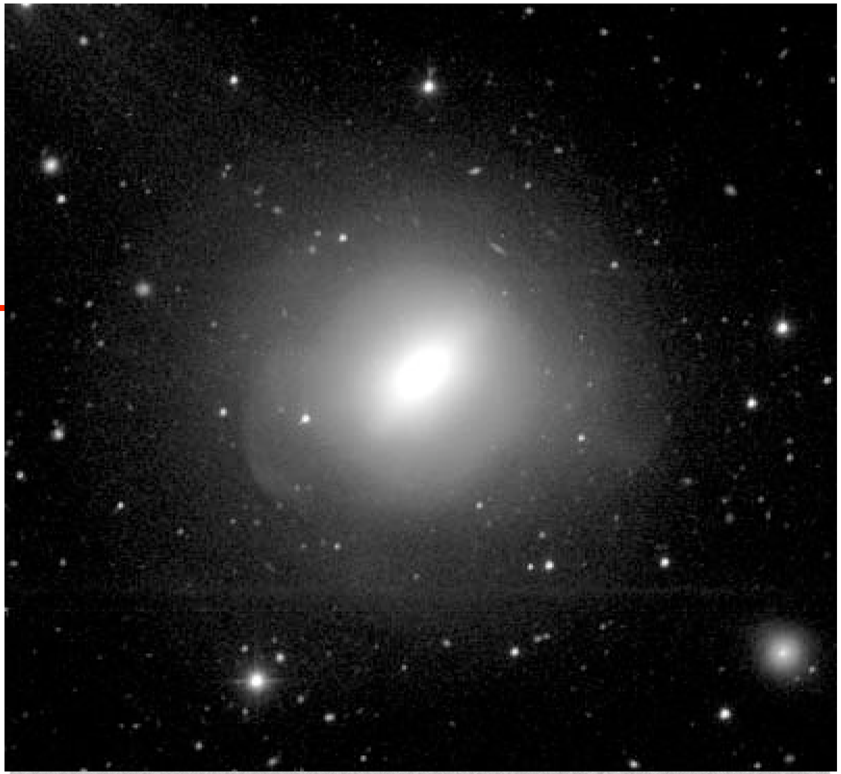
- Increasing evidence that both red and blue globular clusters are very old (>10 Gyr)
- Small percentage of red globular clusters may be young
- Ellipticals/Lenticulars:

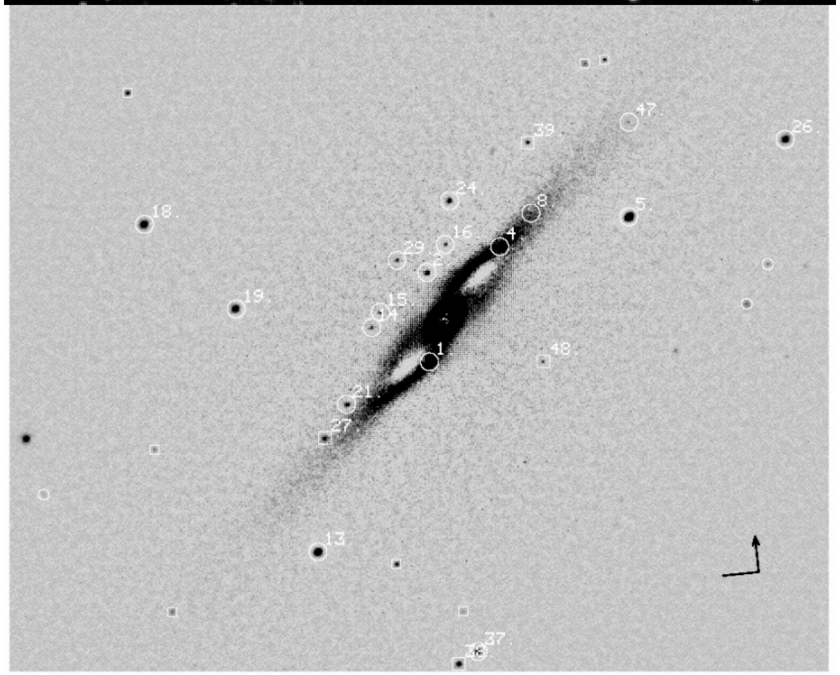
  NGC 1399 (Kissler-Patig, et al. 1998; Forbes et al 2001)
  M87 {Cohen, Blakeslee & Ryzhov 1998}
  NGC 4472 (Puzia et al 1998; Beasley et al. 2000)
  NGC 1023 (Larsen & Brodie 2002)
  NGC 524 (Beasley et al 2003)
  NGC 3610 (Strader et al 2003, 2004)
  NGC 4365 (Larsen et al 2003, Brodie et al 2005)
  NGC 1052 (Pierce et al 2004)
  NGC 7457 (Chomiuk, Strader & Brodie 2005)
  NGC 1407 (Cenarro et al. 2005)
  NGC 5128 (Beasley et al. 2005)
  + various dwarfs (e.g. VCC 1087 Beasley et al 2005)
- Spirals: M 31 (Barmby et al. 2000; Beasley et al 2004, 05)
  M 81 (Schroder et al 2001)
  M 104 (Larsen et al 2002)

NGC 3610

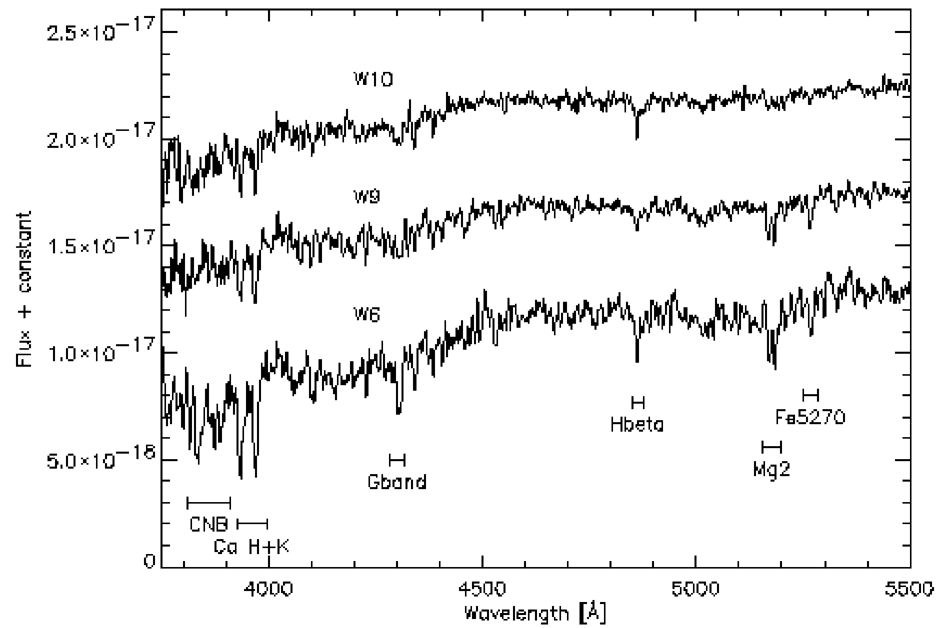
- Intermediate age (2–4 Gyr) merger remnant
- Keck spectra of 6 candidate young clusters (+ 2 with bluer colors)
- $3 < R_g < 13$ kpc
  $R_{eff3610} = 2.3$ kpc

Strader, Brodie, Schweizer (2003)





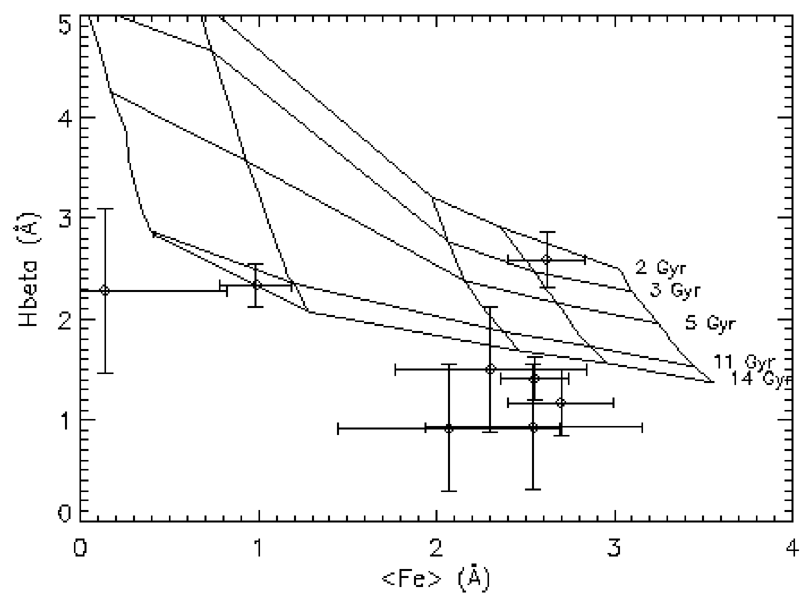
NGC 3610
Spectra + Models



3 distinct sub-groups:

- old and metal-poor
- old and metal-rich
- single metal-rich young (~ 2 – 4 Gyr) cluster!

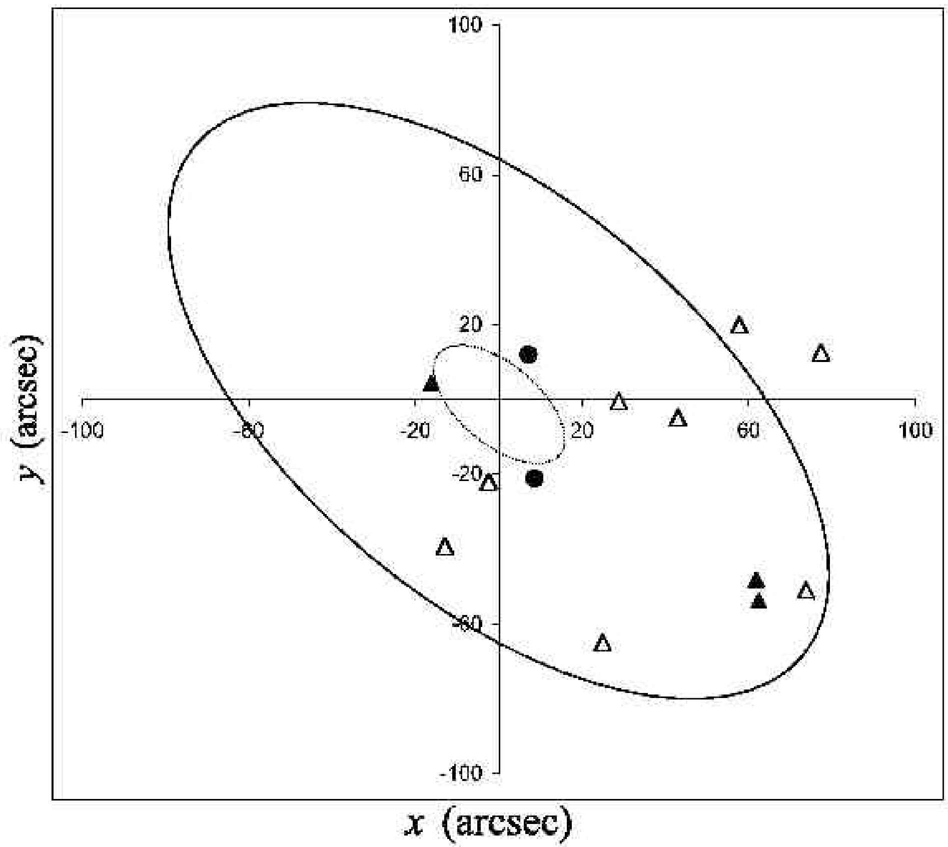
Within errors, all 7 old clusters are coeval

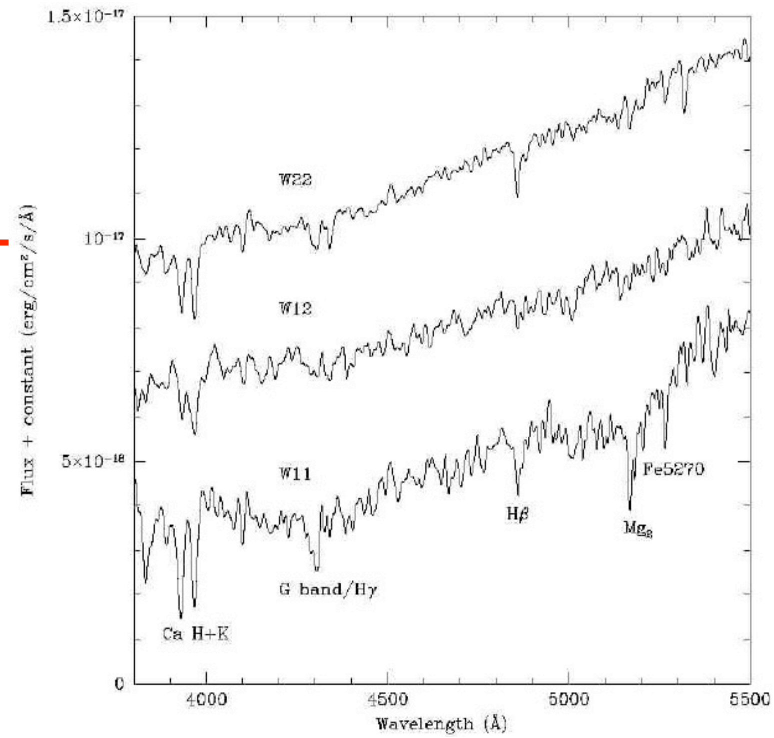


Strader, Brodie, Schweizer (2003)

New Sample

- Now 13 confirmed GCs
  9 within one K-band R_{eff}

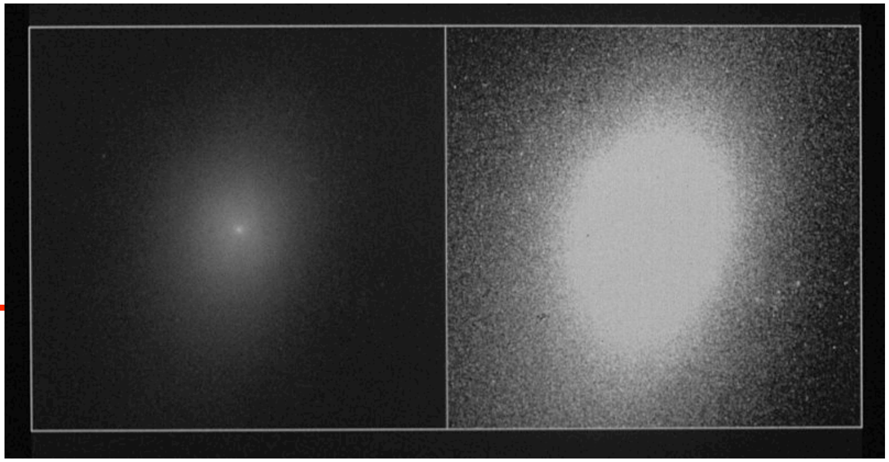




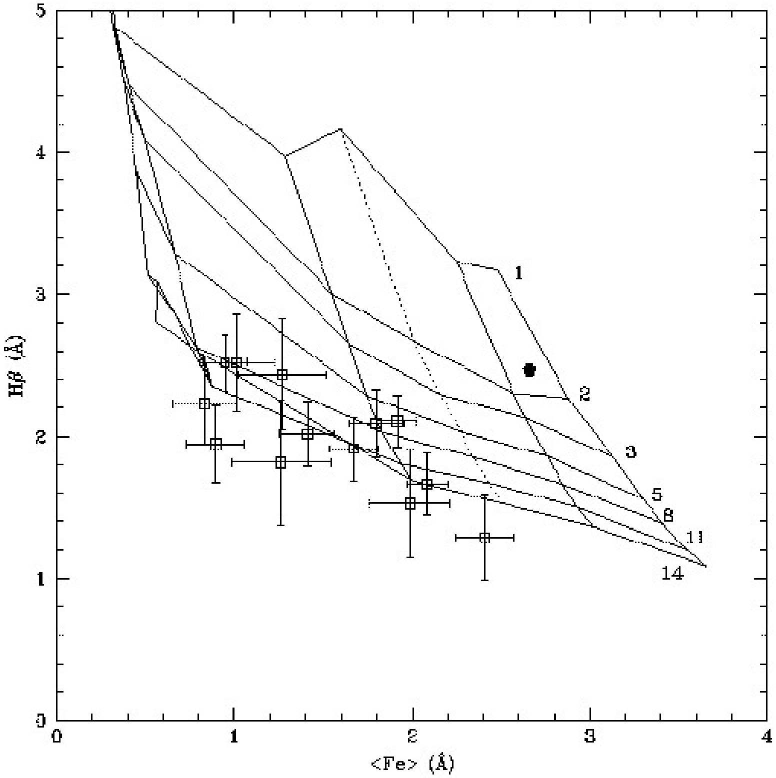
- 3 old and and metal-poor
- 8 old and metal-rich
- 2 young (~2 Gyr) and metal-rich ([Z/H]~+0.5)
- Young clusters consistent with galaxy age (1.6±0.5 Gyr) and metallicity ([Z/H]~+0.6)

(Strader, Brodie & Forbes 2004)

NGC 7457



- S0 at 12.2 Mpc
- Merger remnant?
- Counter-rotating core
- Central age 2–2.5 Gyr (Sil'chenko et al 2002)
- Both subpopulations are old!

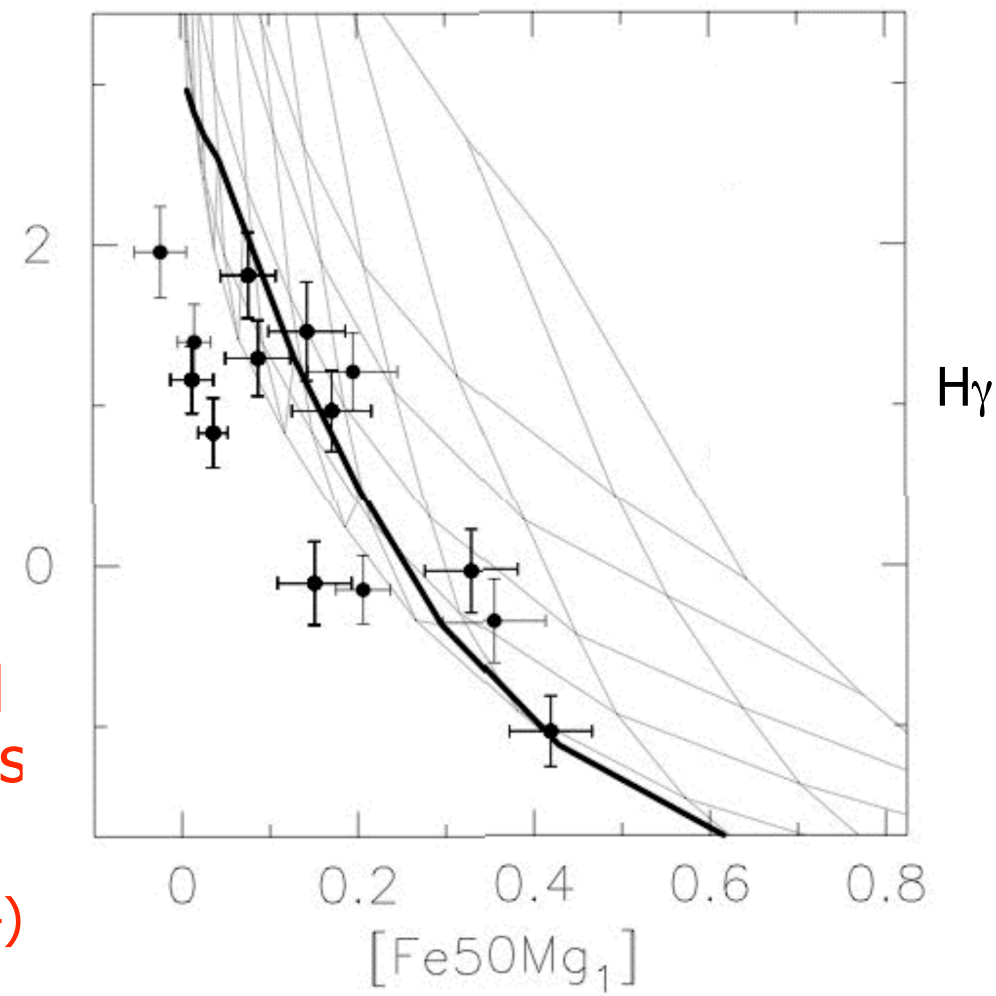


Chomiuk, Strader & Brodie 2005

NGC 1052

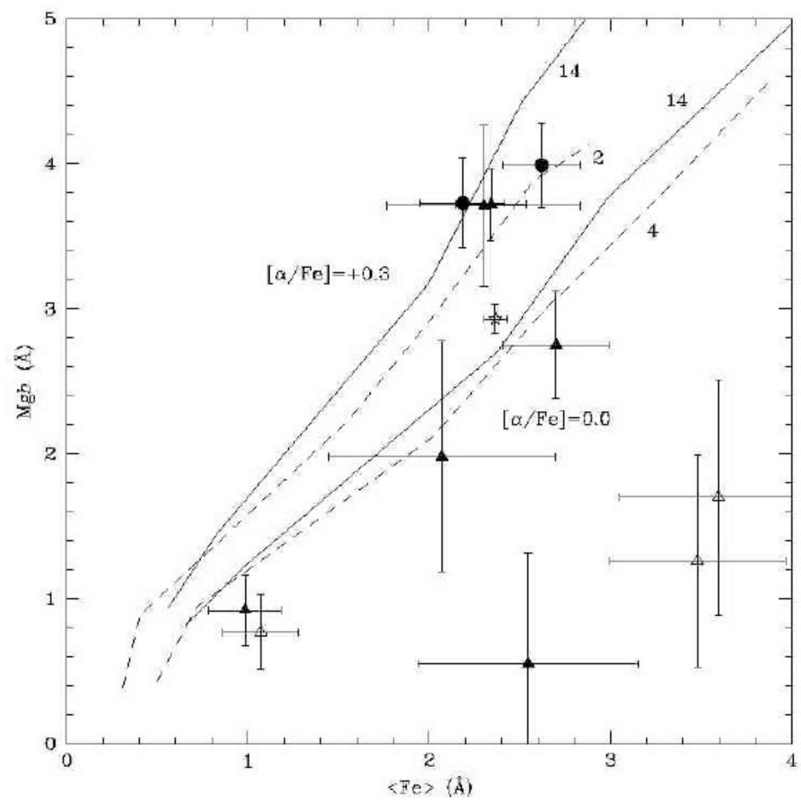
- Merger remnant elliptical in small group at 18 Mpc
- HI tidal tails, HI infalling onto AGN
- Normal on fundamental plane!
- Spectroscopic age ~2 Gyr
- [Fe/H] ~+0.6
- All 16 GCs are ~13 Gyr old with a range of metallicities

Pierce, Brodie, Forbes et al (2004)



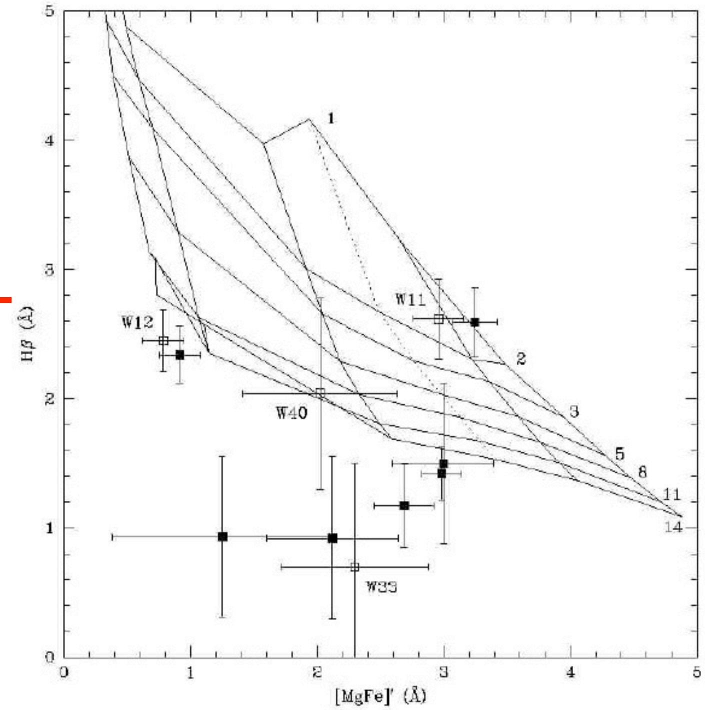
Alpha Enhancement

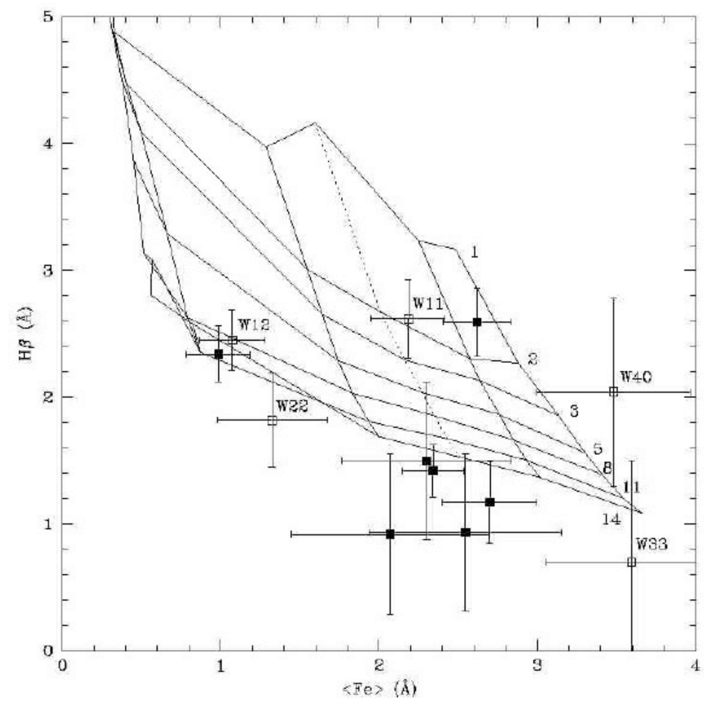
- The two young clusters are alpha-enhanced
- These young GCs are very metal-rich
- Difficult to raise [alpha/Fe] from solar
- Only two old GCs have the alpha enhancement typical of MW GCs



Cluster Census

- 13 confirmed GCs
- 3 old and and metal-poor
- 8 old and metal-rich
- 2 young (~2 Gyr) and metal-rich ([Z/H]~+0.5)
- Ages of young clusters consistent with galaxy age/metallicity estimates of 1.6±0.5 Gyr, [Z/H]~+0.6 (Denicolo et al 2004)





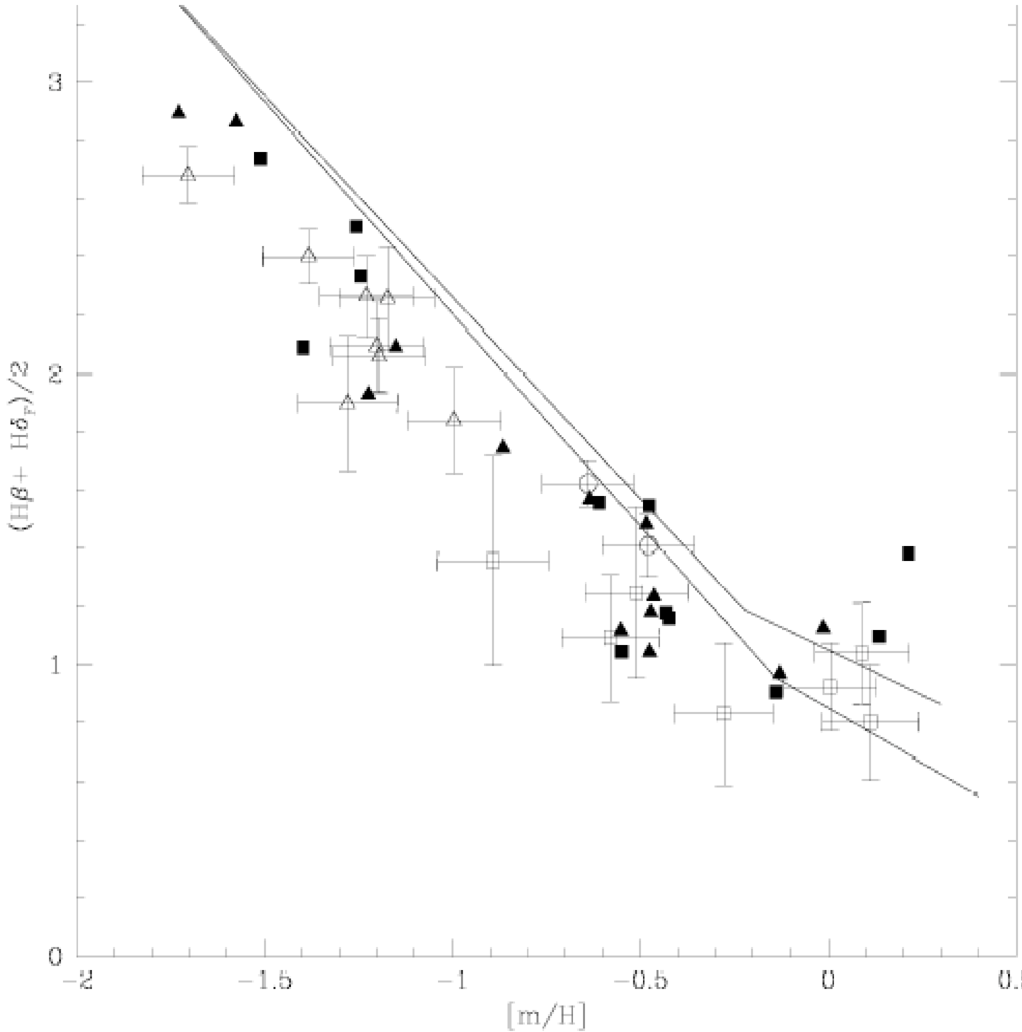
Superglob!

Combining our best data (S/N >30) we find both red and blue sub-pops are ~12 Gyr old, coeval to within the errors

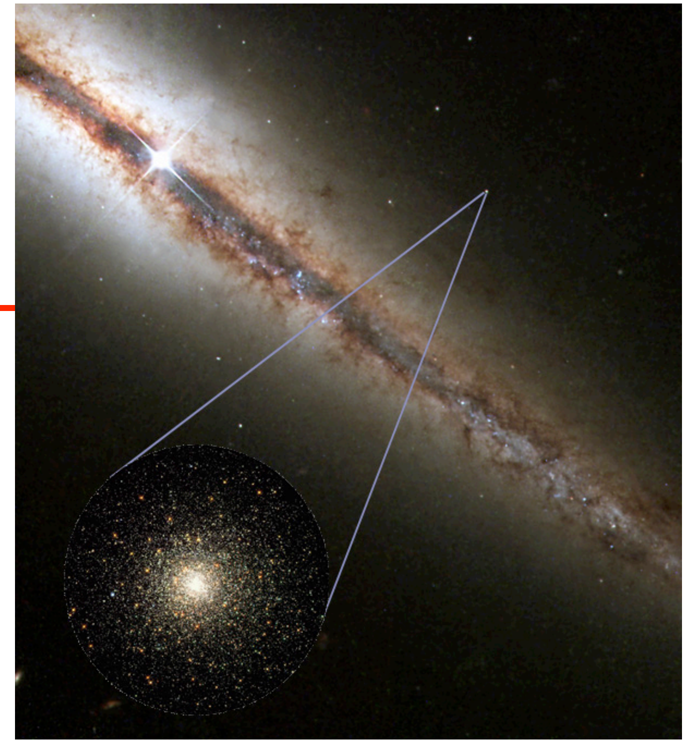
Even in recent merger remnants – rules out (recent) major merger model

Most of the star formation in galaxies happened at high z (>2)

Strader, Brodie, Cenarro Beasley & Forbes (2005)



Spirals vs Ellipticals



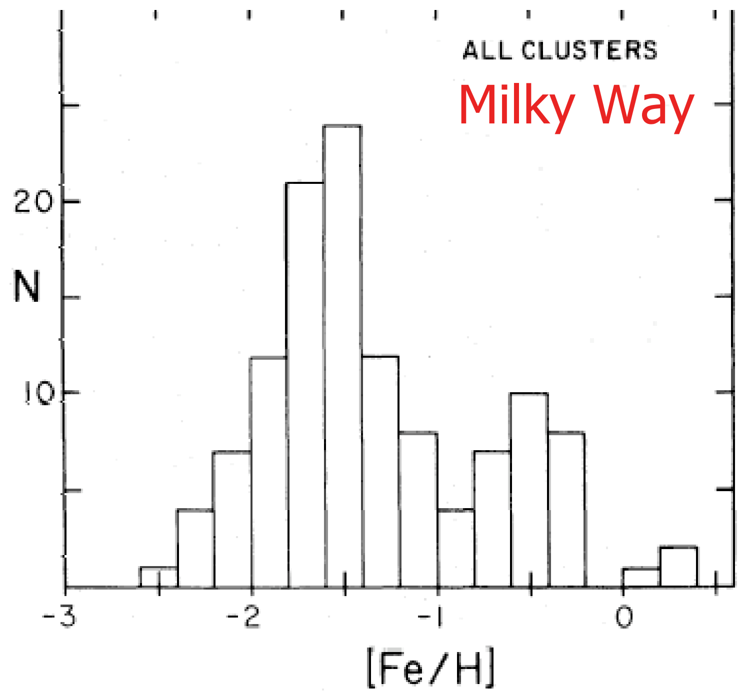
Surveys of early type galaxies

- Average blue peak color $(V-I)_o$=0.95 ±0.02
- Average red peak color $(V-I)_o$=1.18 ±0.04

(Larsen, Brodie, Huchra, et al 2001;
Kundu & Whitmore 2001))

[Fe/H]= – 1.4, –0.6

(Kissler-Patig, Brodie, Schroder etal '98)



Milky Way

Peaks at

[Fe/H] ~ – 1.5 and – 0.6

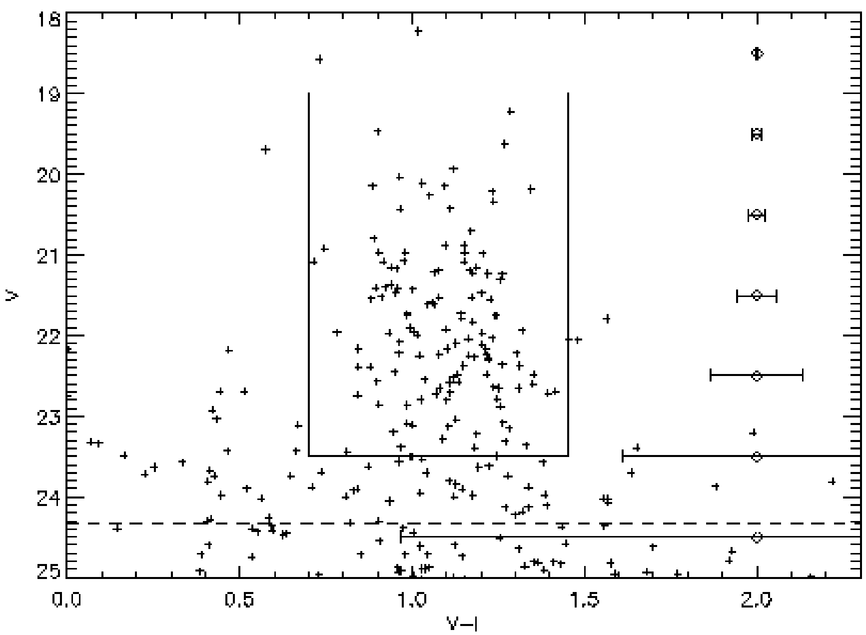
(Zinn 1985)

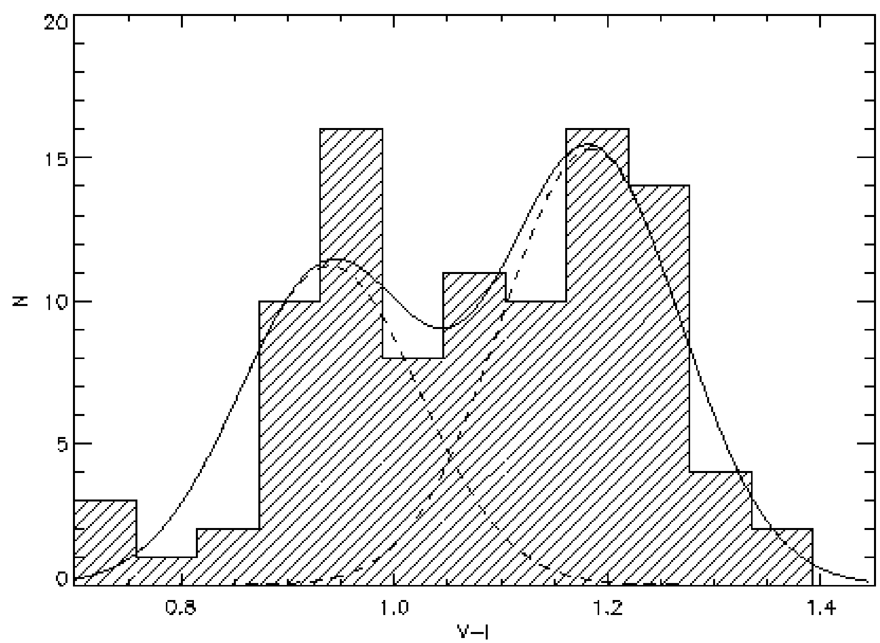
MW GCs are all old

Sombrero

Peaks at $(V\text{–}I)_0$=0.96 and 1.21

Larsen, Forbes & Brodie (MNRAS 2001)





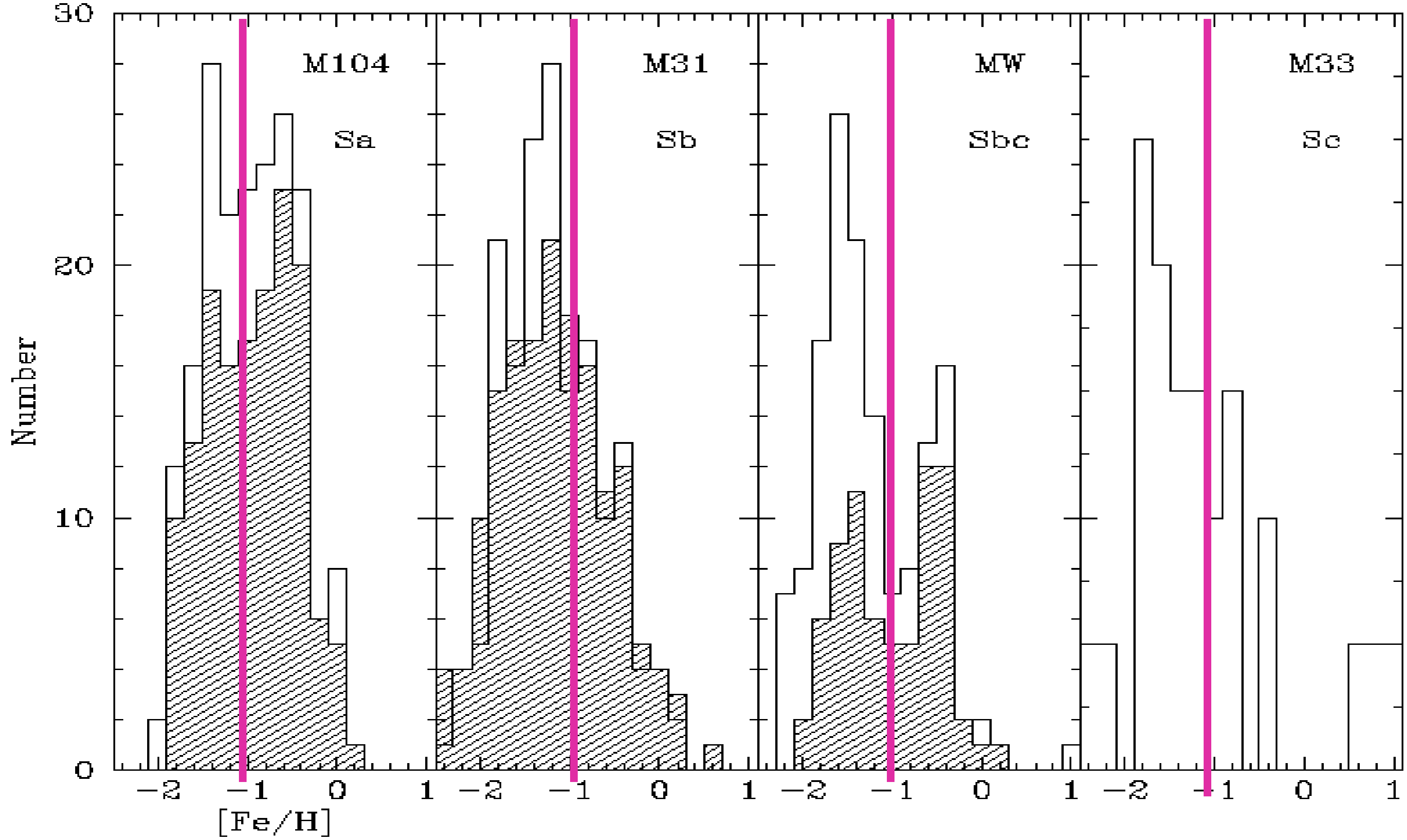
Follow-up spectroscopy at Keck indicates vast majority of GCs (both red and blue) are old (~13 Gyr)

Larsen, Brodie, Forbes (2002)

Bulge GCs

- MR GCs in spirals are associated with the bulge not the disk
- Spirals and field Es have similar #s of MR GCs per unit (bulge) starlight: S_N~1

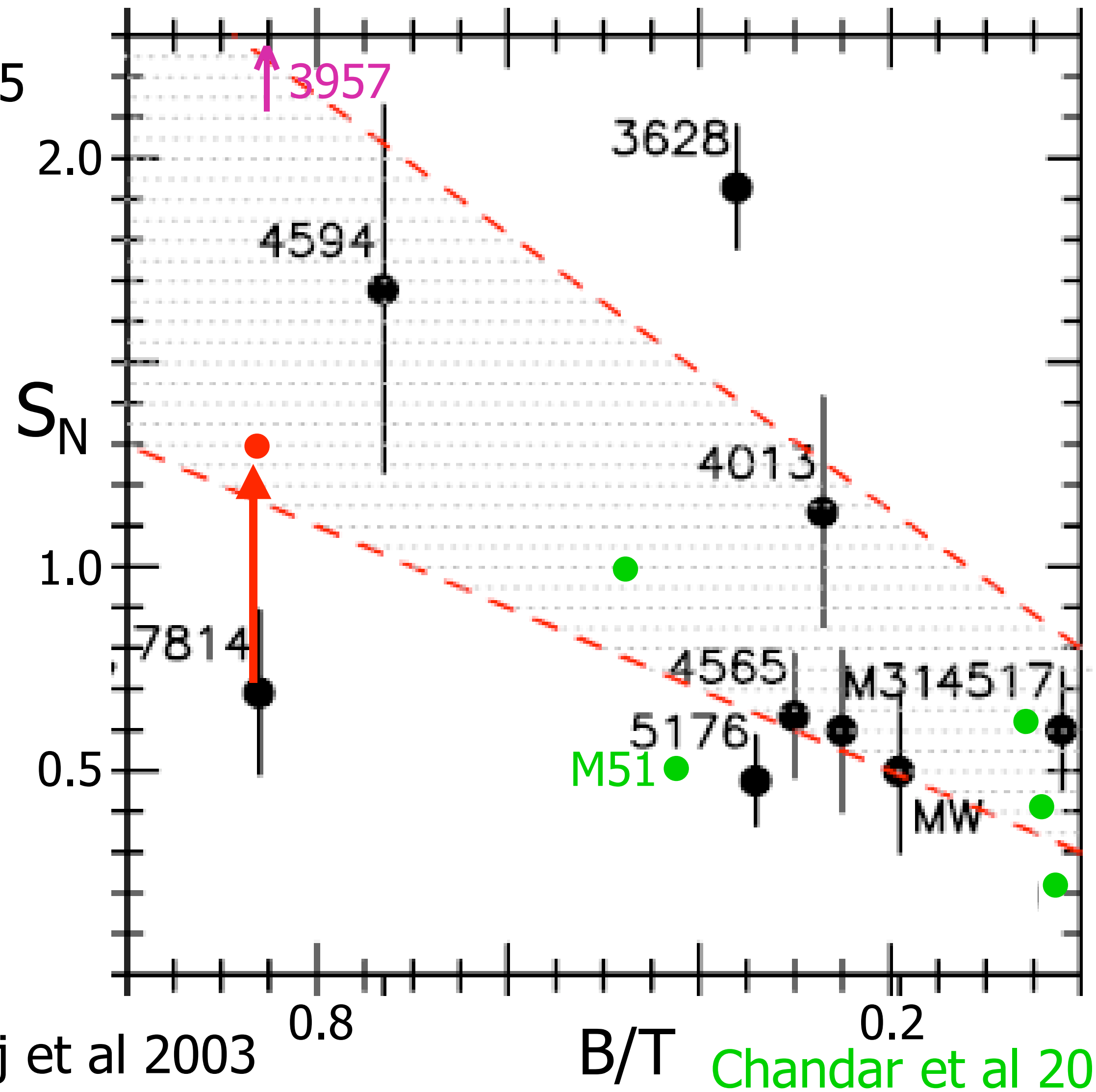
Number of metal-rich GCs scales with the bulge & metal-rich GCs are old – argues against secular evolution



Forbes, Brodie & Larsen ApJL (2001)

Specific Frequency

- S_N (total) constant at ~0.55 for spirals with B/T≤0.3 (Sb and later)
- Constant number of GCs formed in late-type spirals
- Universal old halo population
- S_N (total) ~ 2 for "field" Es
- If higher S_N for Es due to "extra" GCs formed with bulge, expect S_N to scale with B/T from ~0.55±0.25 at B/T=0 to ~1.9±0.5 at B/T=1



Goudfrooij et al 2003

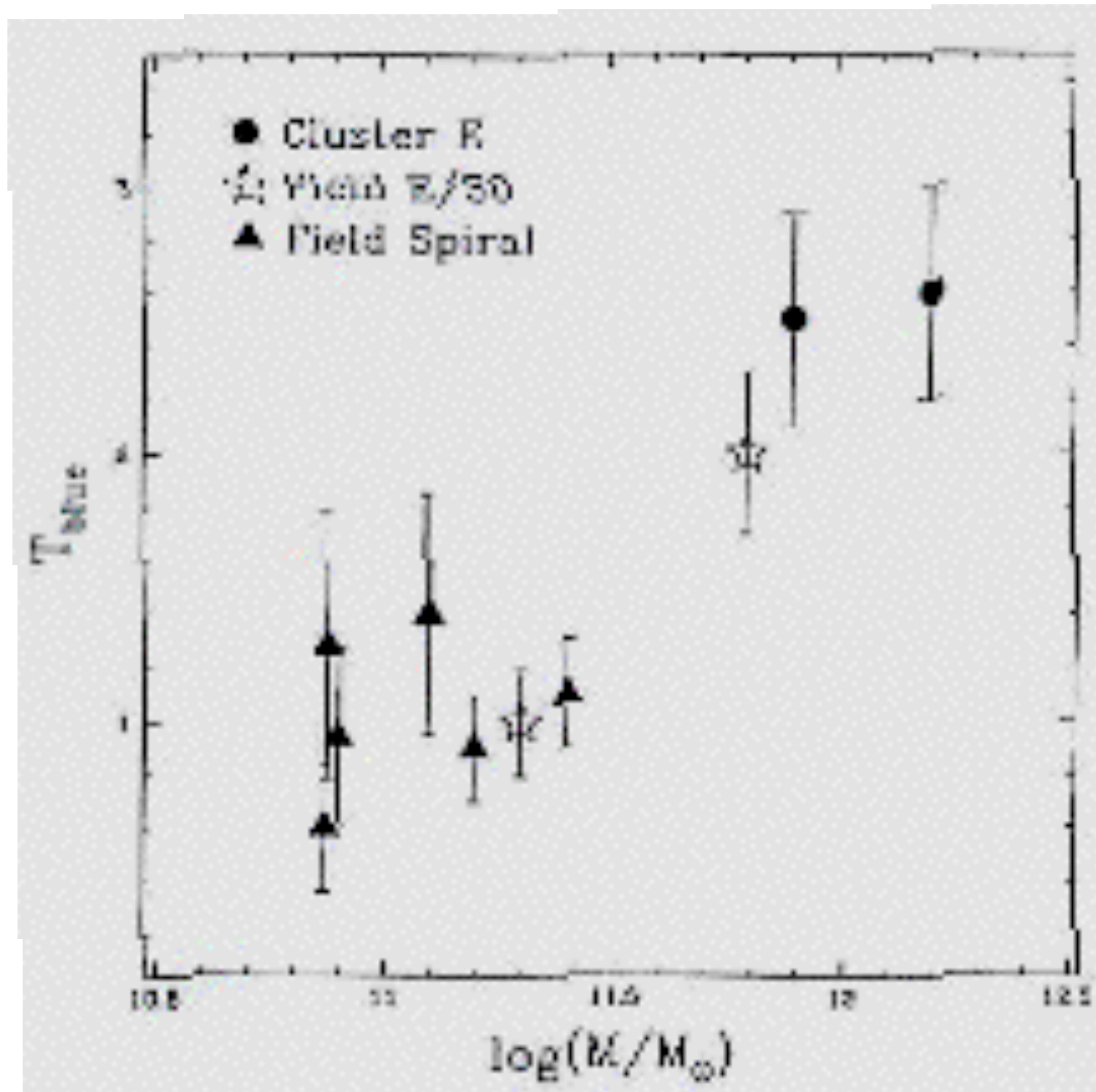
Chandar et al 2004

Exceptions

- NGC 3628: Interacting
  HI tidal plume + bridge connection with
  NGC 3627 – extra GCs formed in interaction?
- NGC 7814: Best evidence for secular evolution?
  Least luminous sample galaxy (5 x less than NGC 4594). Satellite-to-main galaxy mass ratios of 10% more common for low mass galaxies
  (Goudfrooij et al 2003)
- M 51: Does it have a bulge?
  Interacting with NGC 5195
  Too few "bulge" (MR) GCs? (uncertain estimate)
  16 vs 98 (bulge/disk deconvolution) or
  16 vs 45 (σ – BH mass) (Chandar et al 2004)

Universal Blue Population?

- Rhode et al (2005) find larger relative numbers of metal-poor GCs with increasing galaxy mass
- Could be flat for spirals



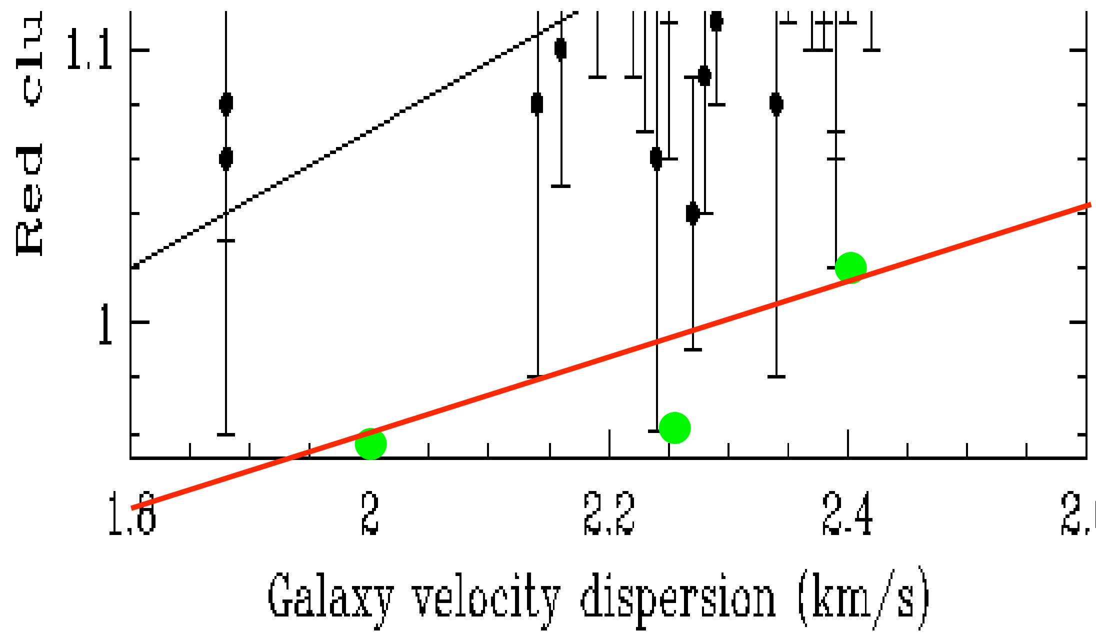
Correlations with parent galaxy properties

Red GC relation has same slope as galaxy color relation ⇒

Red GCs and galaxy stars formed in the same star formation event

Metal-rich GCs in spirals and ellipticals have the same origin — they formed along with the bulge stars

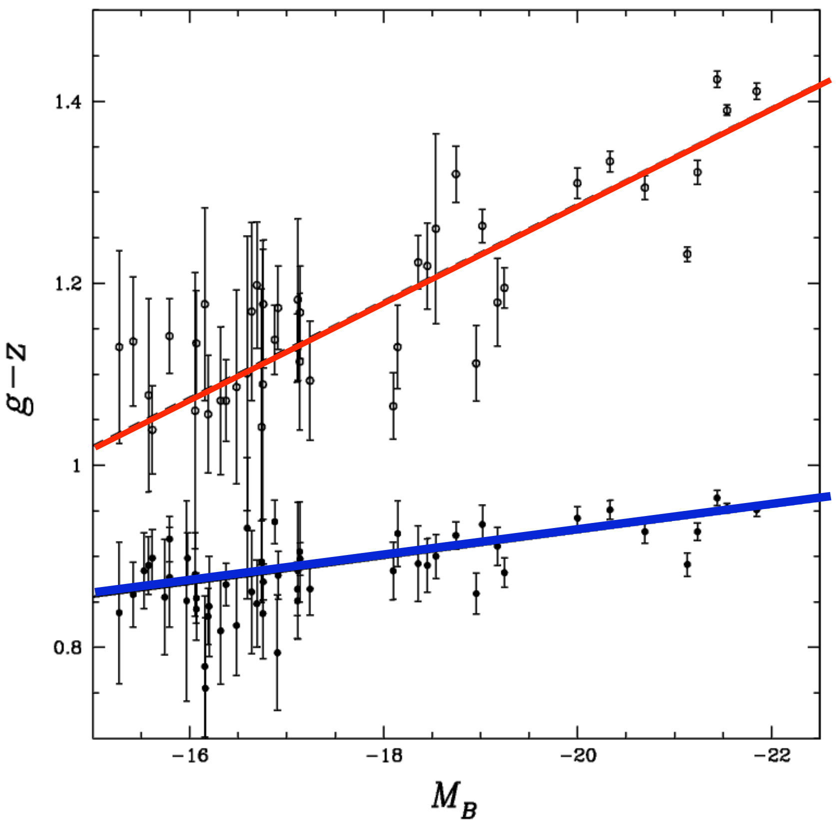
Spirals fit the trend

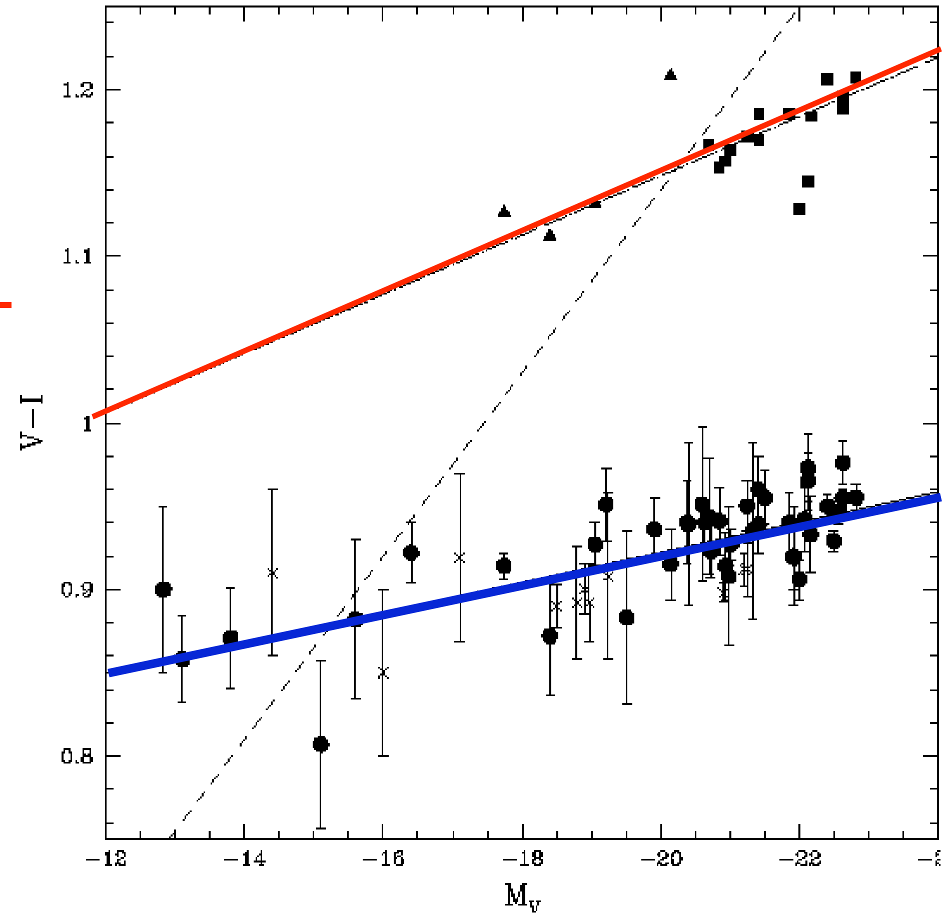


Brodie & Huchra 1991; Forbes, Brodie & Grillmair 1997; Forbes, Larsen & Brodie 2001; Larsen, Brodie, Huchra et al 2001

Correlations with parent galaxy properties

- Colors of *both* reds and blues correlate with galaxy mass and color



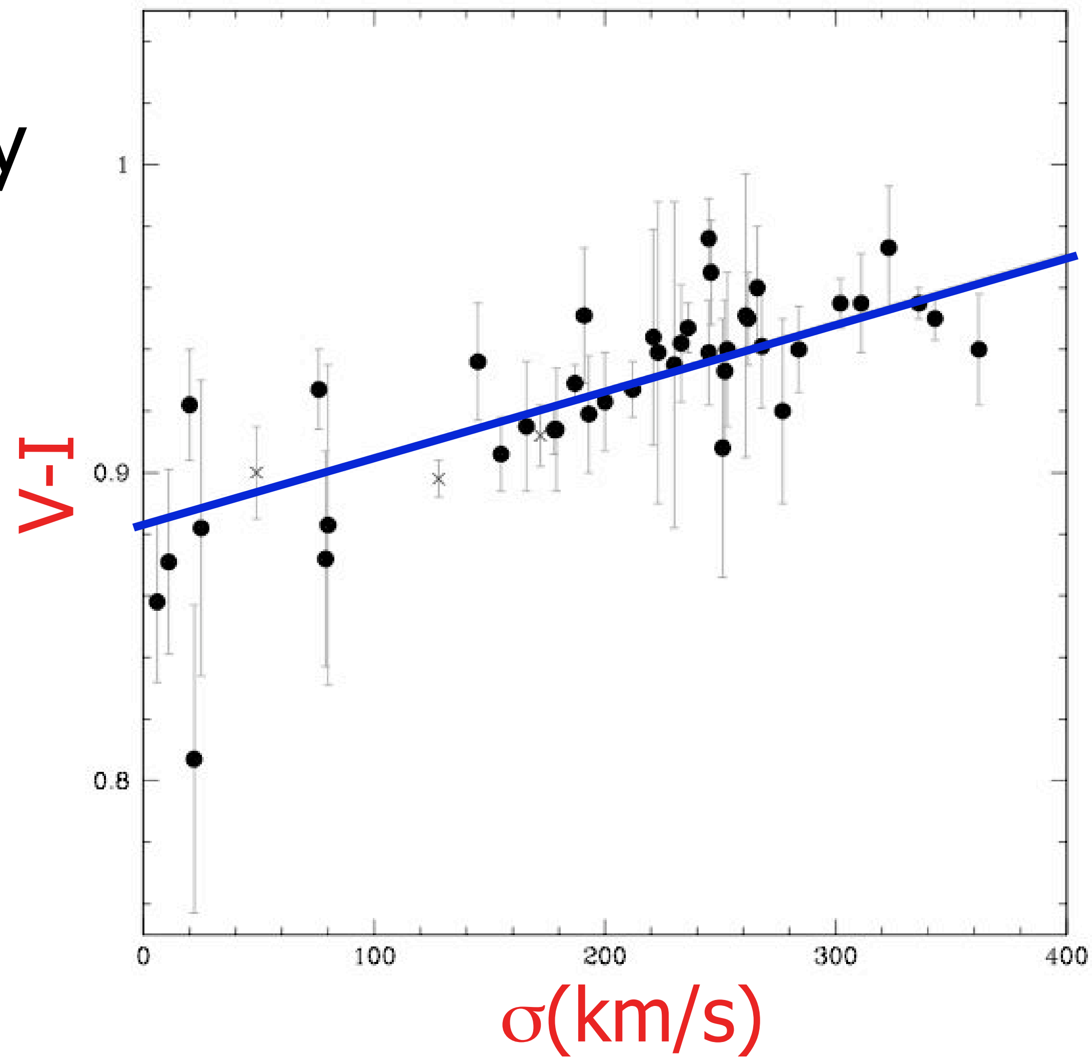


- Blue relation difficult to explain under accretion/major merger scenarios
- Constraints on Hierarchical Merging Paradigm

Strader, Brodie, Cenarro & Beasley (2005)
Strader, Brodie & Forbes (2004)
Larsen, Brodie, Huchra et al (2001)

Work in progress……..

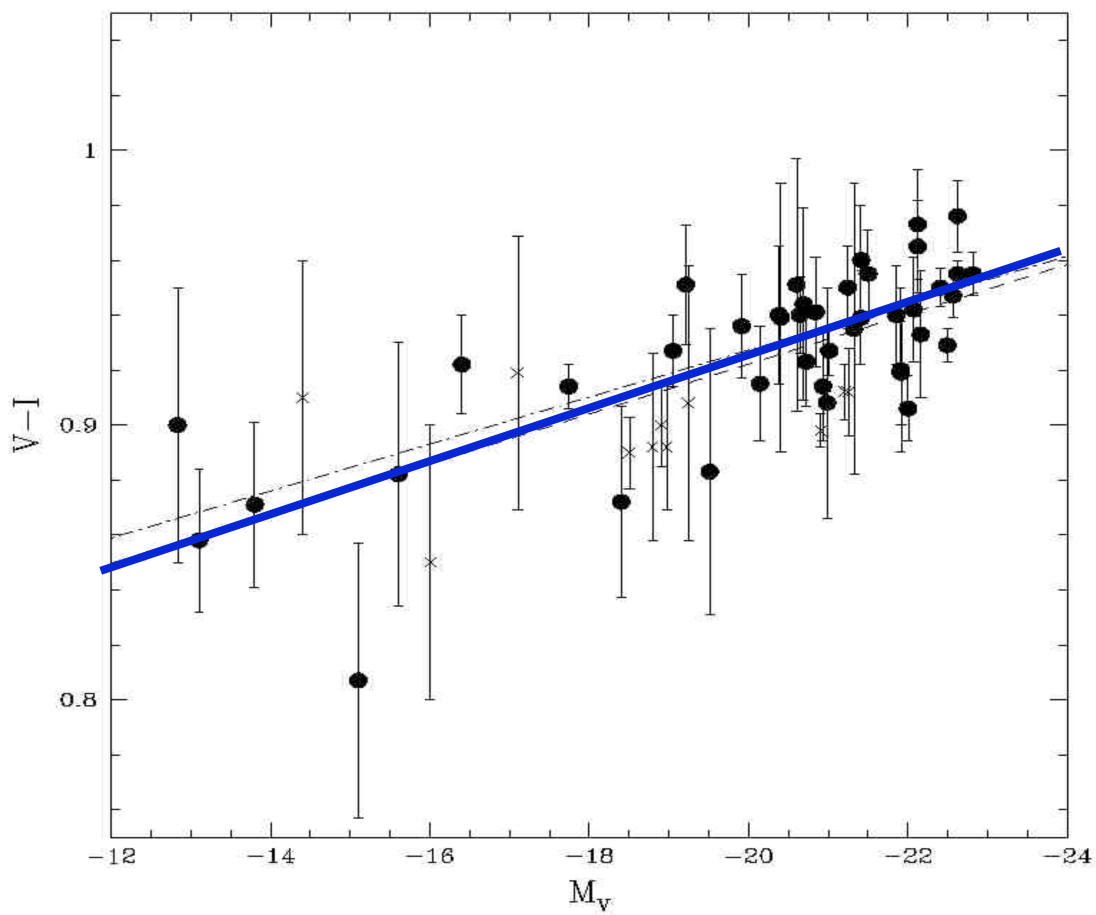
Even more highly significant with σ as a proxy for mass!

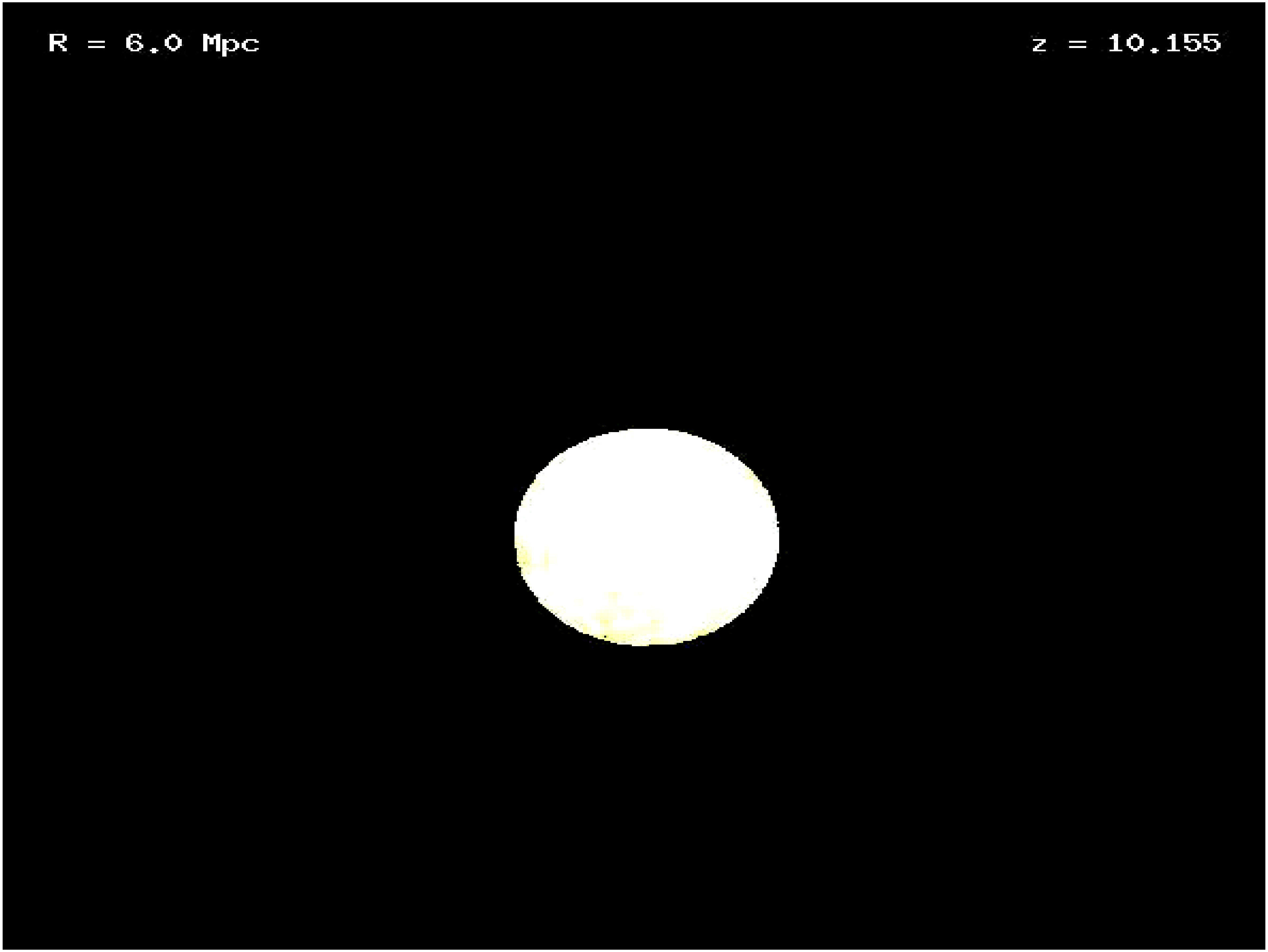


Blue Globular Clusters

Strader, Brodie & Forbes 2004

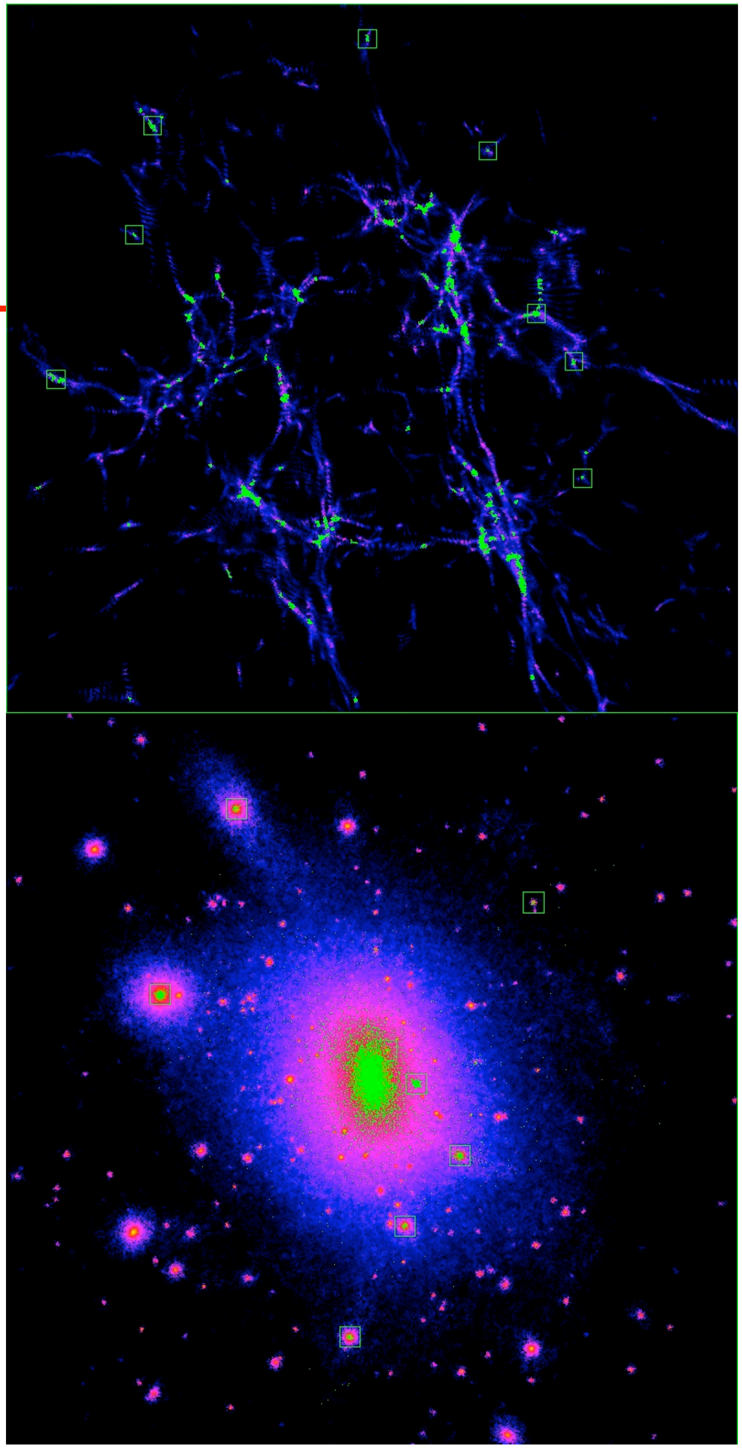
Disk galaxies *may* have systematically bluer metal-poor GC systems ~0.1 dex ⇒ larger gas fraction at time of blue GC formation ⇒ metal-poor GCs in disk galaxies are older or chemical enrichment to 0.05-0.03 Z_{SUN} was faster in ellipticals




R = 6.0 Mpc
z = 10.155

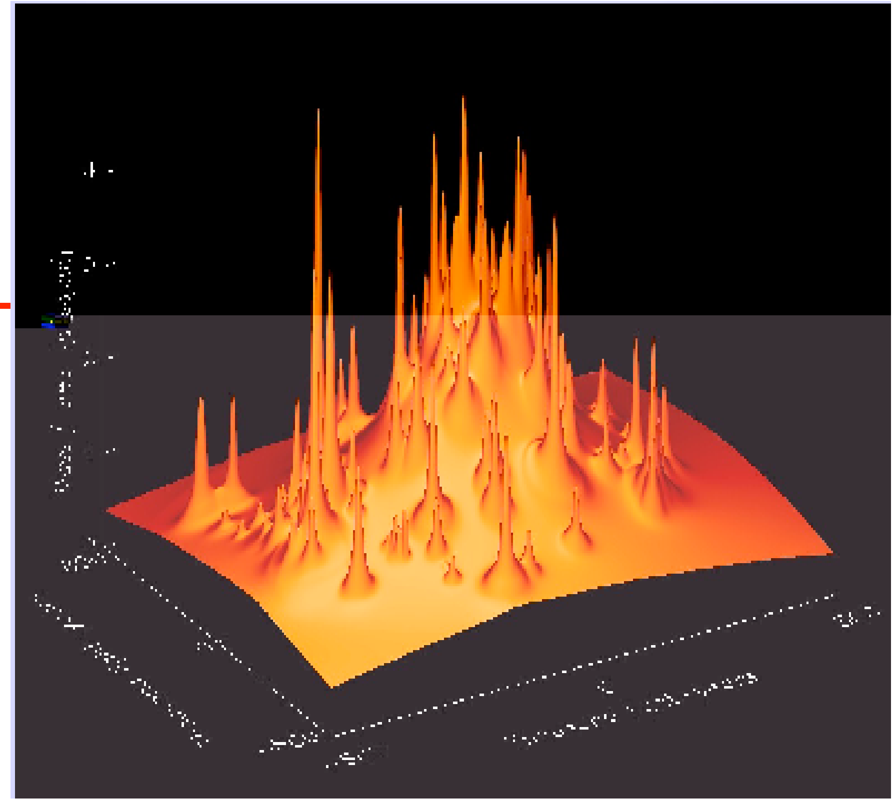
ΛCDM

- N-body simulations suggest that dark matter halos "sitting" on top of large overdensities collapse first (z~18??)
- The majority of these halos combine to form massive galaxies at z=0



Courtesy
Juerg Diemand

New "synthesis" formation scenario



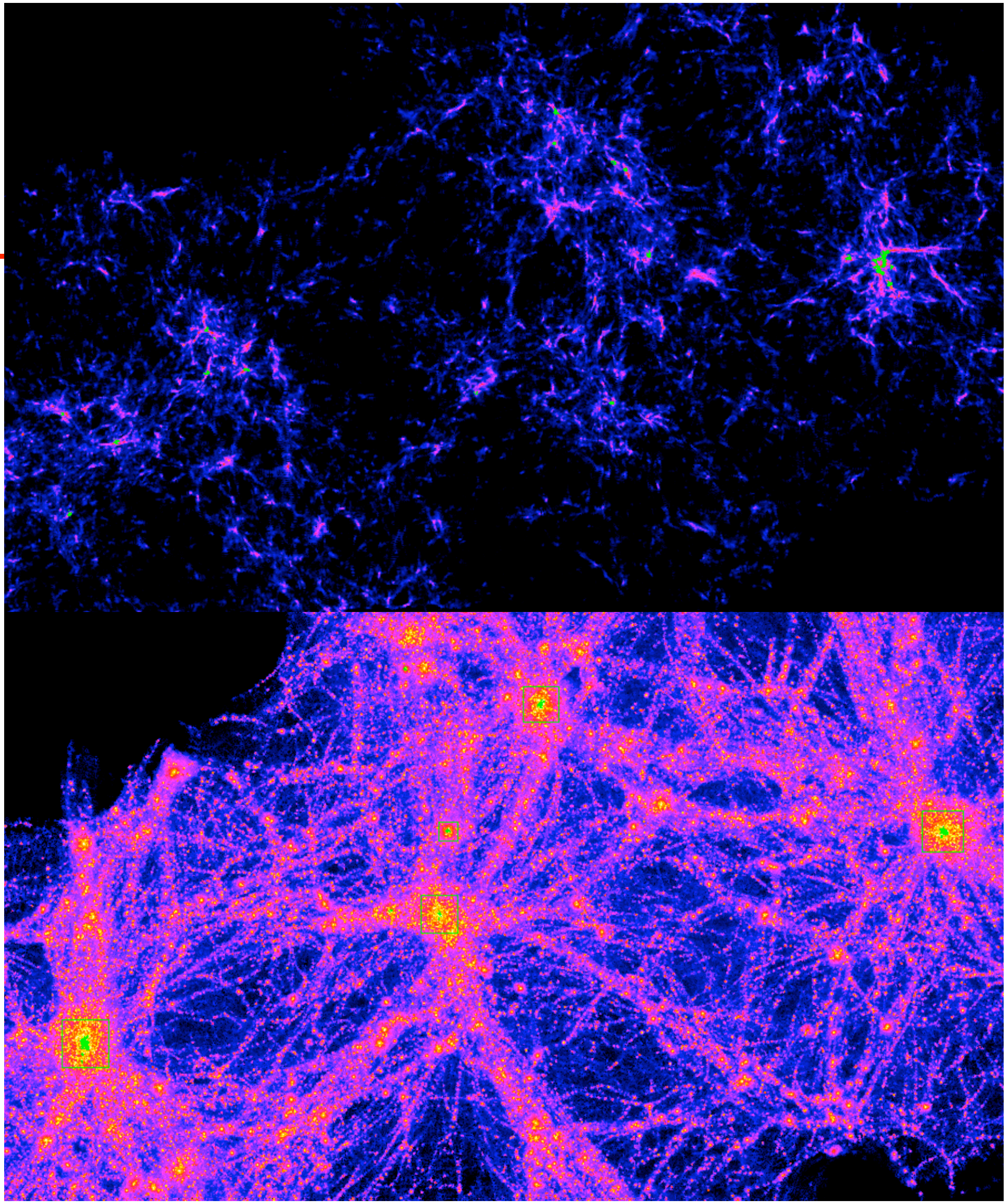
- "Biasing" makes low mass halos on top of large overdensities collapse before those on periphery
- Reionization truncates blue (MP) GC formation
- Halos that collapse first produce MP GCs of higher metallicity
- Halos in close proximity to massive parent halo produce the MP subpopulation of resulting luminous galaxy
- More distant halos survive independently to become dwarf galaxies

Strader, Brodie, Cenarro, Beasley & Forbes AJ 2005

GC surface density distributions ⇒ epoch and (in)homgeneity of reionization   Moore et al Nature (2005)

Cosmic Web

- Do blue GCs trace the cosmic web?
- Alignment of blue GC distributions
- Dwarf galaxies more pristine tracers?



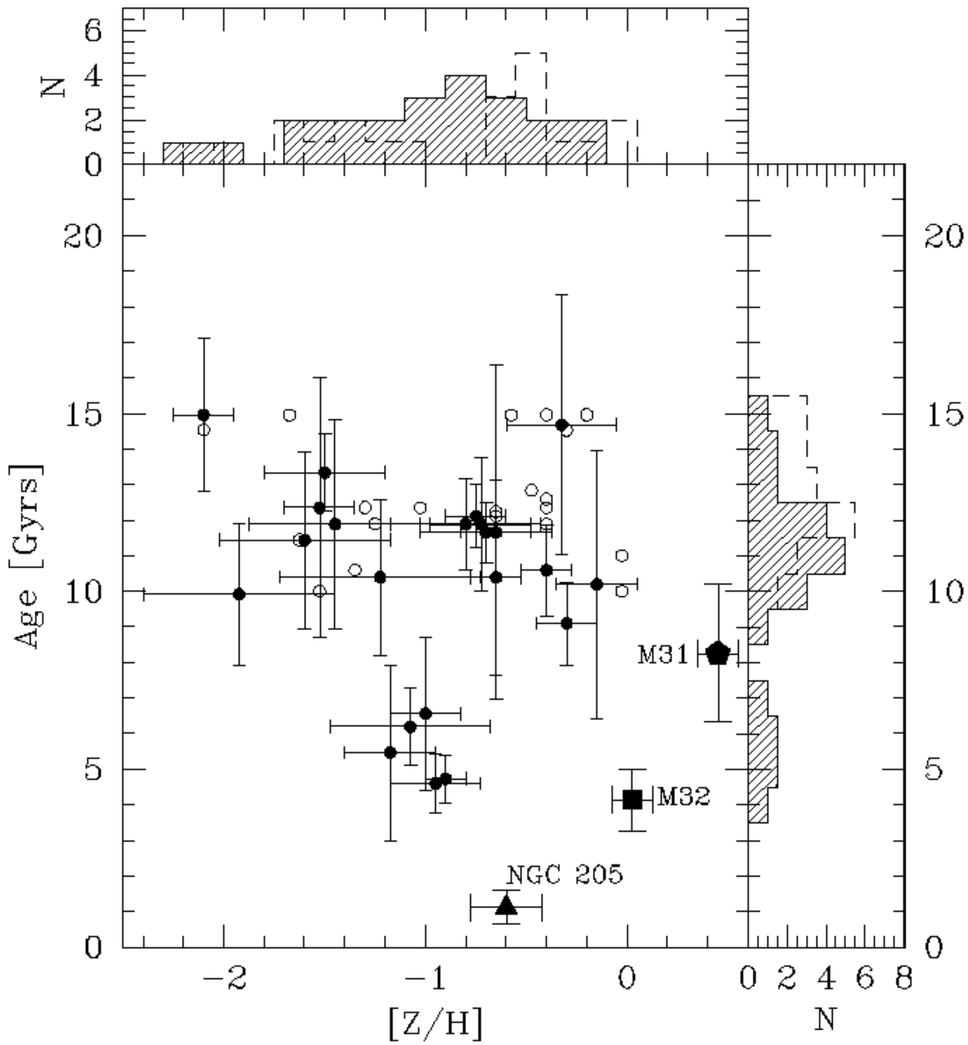
Courtesy Juerg Diemand

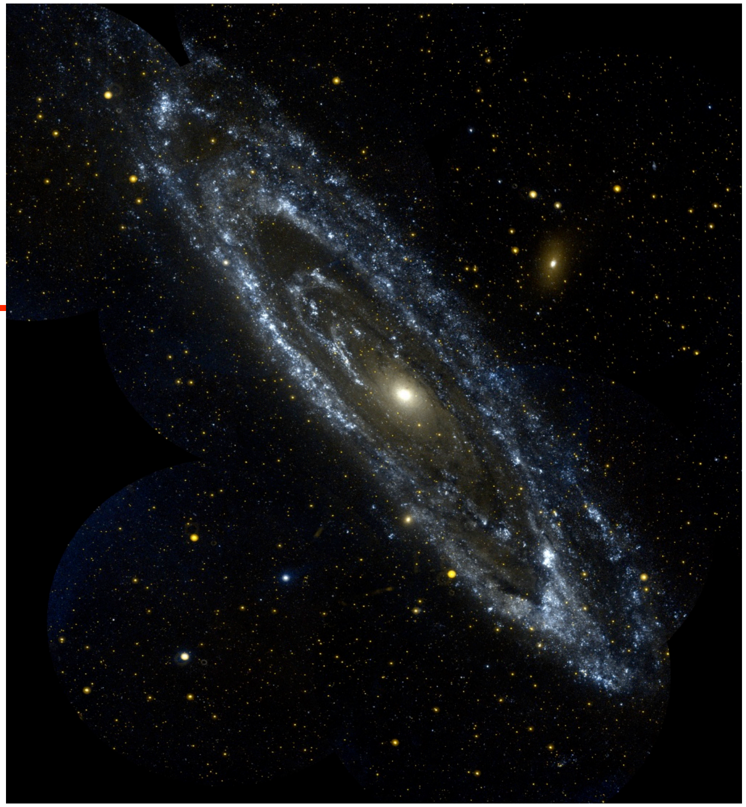
GC–Field Star Connection

- MP GCs appear to have formed with significantly higher (factor >10) specific frequencies than MR GCs
- Degree to which this varies from galaxy to galaxy is unknown (e.g. NGC 5128 & M31 vs MW)
- Consistent with idea that GCs formed early in star forming episodes
- In the truncation (reionization?) scenario, star formation was cut off after significant blue GC formation but before much star formation
- Observational evidence suggests that MP GCs formed in halos with a minimum mass of $\sim 10^7$–10^8 M_{SUN}
- Connection to DM halo masses at earliest epochs?

M 31 Multiple GC Pops

Beasley et al 2004, 2005



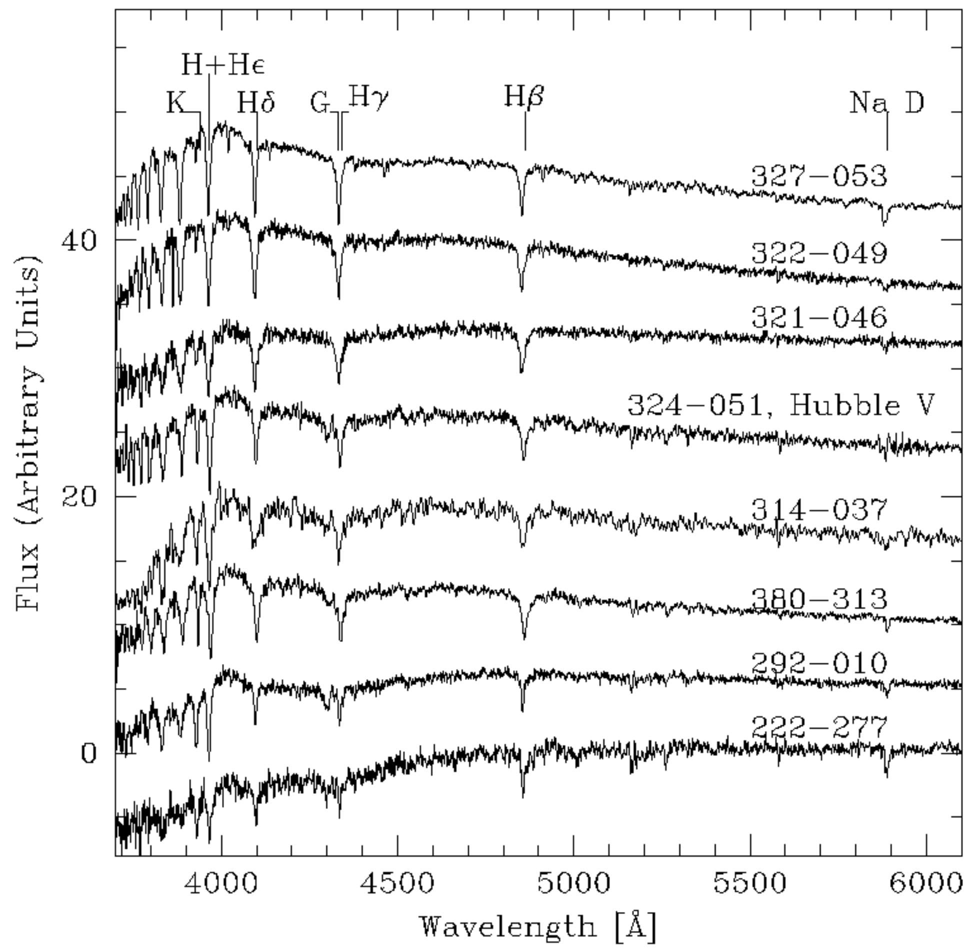


- High S/N Keck spectra of 30 M31 GCs
- 4 distinct populations: MP old (7), MR old (10), MR young (7), Intermediate age/metallicity (6)
- 3 – 6 Gyr, [Z/H] ~ –1 No analog in MW
- Origin in accreted gas-rich dwarf?

Do GCs trace the build up of disks?

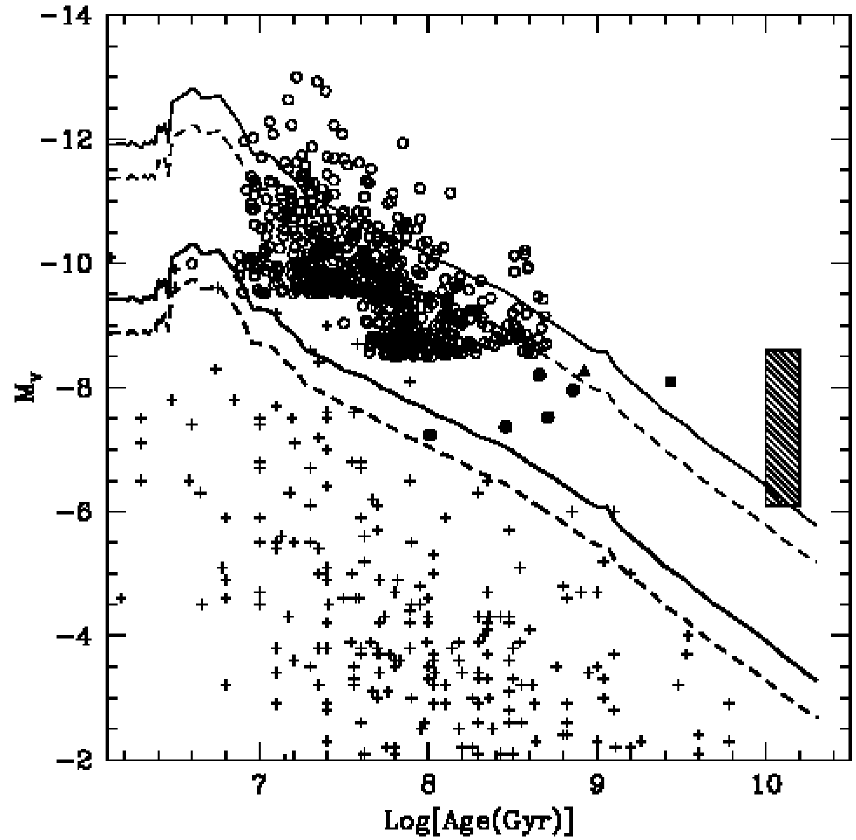
M31 Young Clusters

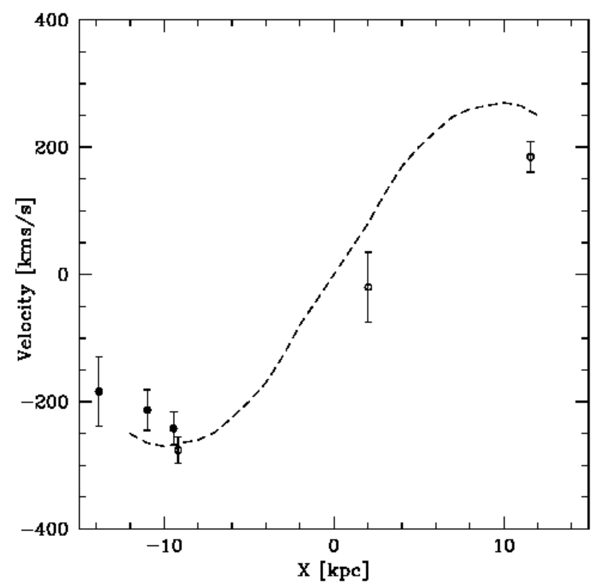
- 6 disk “GCs”
- – 0.20<[Fe/H]<– 0.3
- Ages 100 – 800 Myr
- 0.7 – ~7.0 x 10^4 M_{sun}



Young MR disk clusters in M31

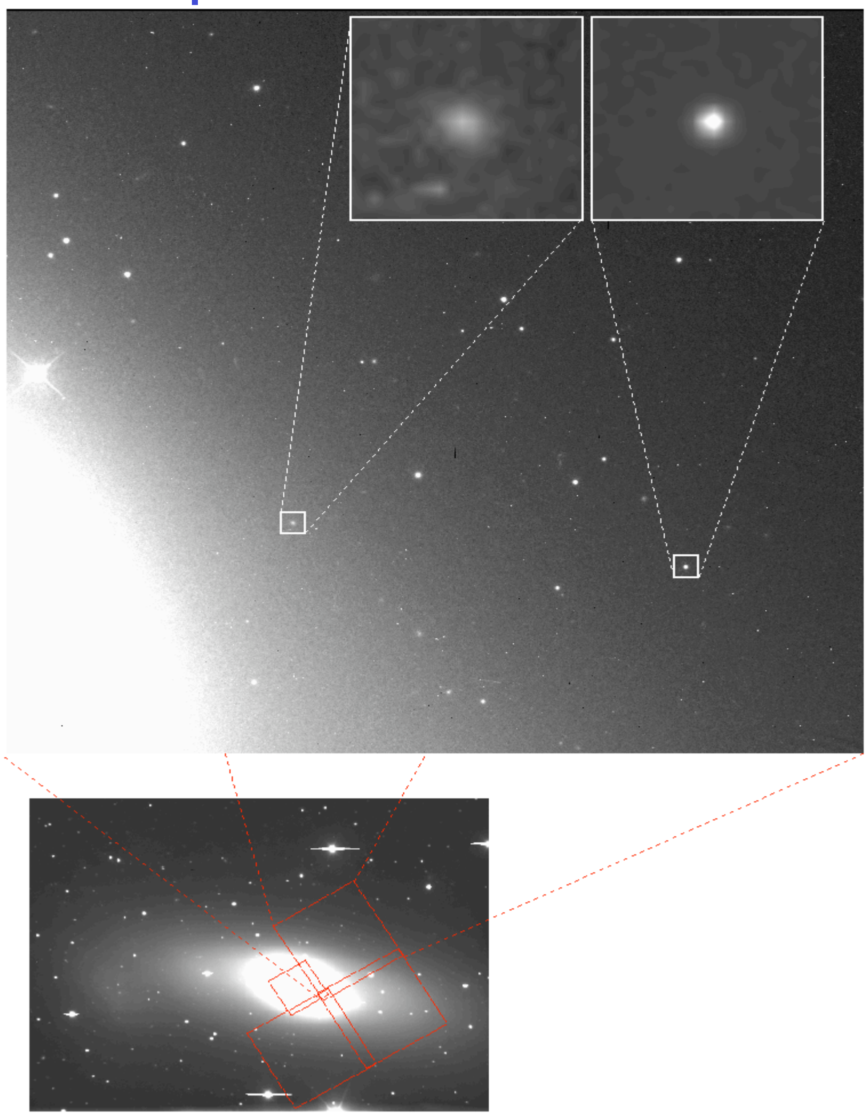
- Subset of Morrison et al's thin disk GCs but MR & young *not* MP & old
- Relaxes accretion constraints
- Globular or open clusters?
- GCs trace build up of galaxy disks?



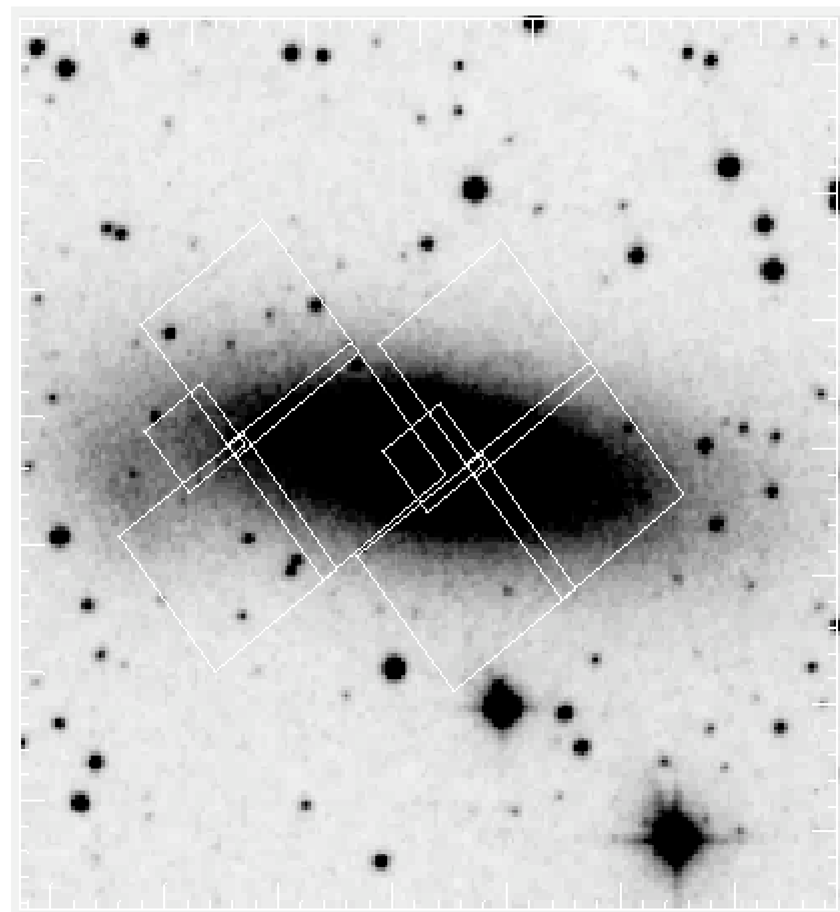


Faint Fuzzies

Burkert, Brodie & Larsen 2005
Brodie & Larsen 2002
Larsen & Brodie 2000



Discovered in HST observations of 2 nearby S0 galaxies



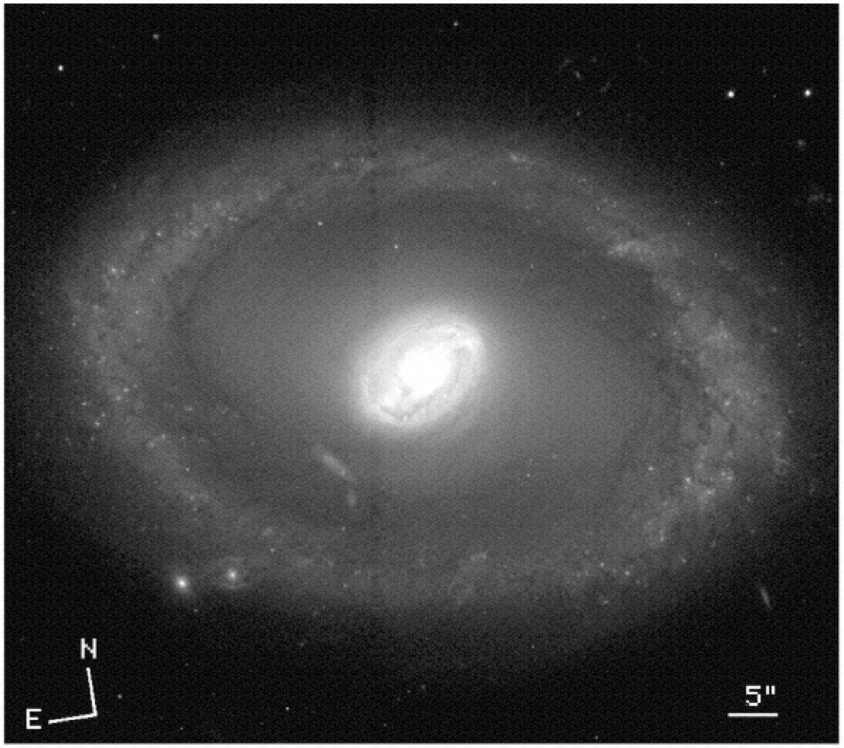
Special formation conditions

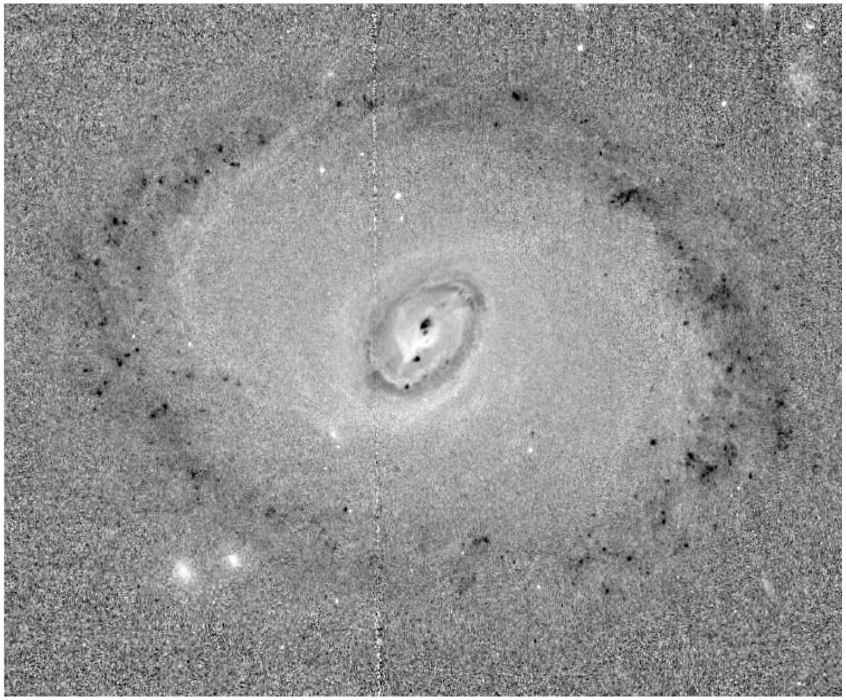
- Old (~13 Gyr), metal-rich, rotating system of extended ($<r_e>\sim 11$ kpc) star clusters
- As a population FFs have no known analogs in the Milky Way or elsewhere in the Local Group
- Formed inside (S0) disks, in a ring, on fast-rotating orbits
- Formation in GMCs? If star formation has density threshold, produces bound clusters with sizes and masses of FFs (Geyer & Burkert 2005)
- These special conditions may occur as a result of galaxy-galaxy interactions or on resonance rings

Resonance Rings

NGC 3081 Buta et al (2004)

- $M_B = -20$ early-type (S0/a, Sa) barred spiral (bulgeless)
- Inner ring encircles bar at ~5 kpc
- ~58 blue (young) clusters in ring with $M_V < -9$ ($V<23.6$) Typical cluster effective radius ~11 pc !
- Will these clusters survive?
- Is bar formation important in forming lenticular galaxies?





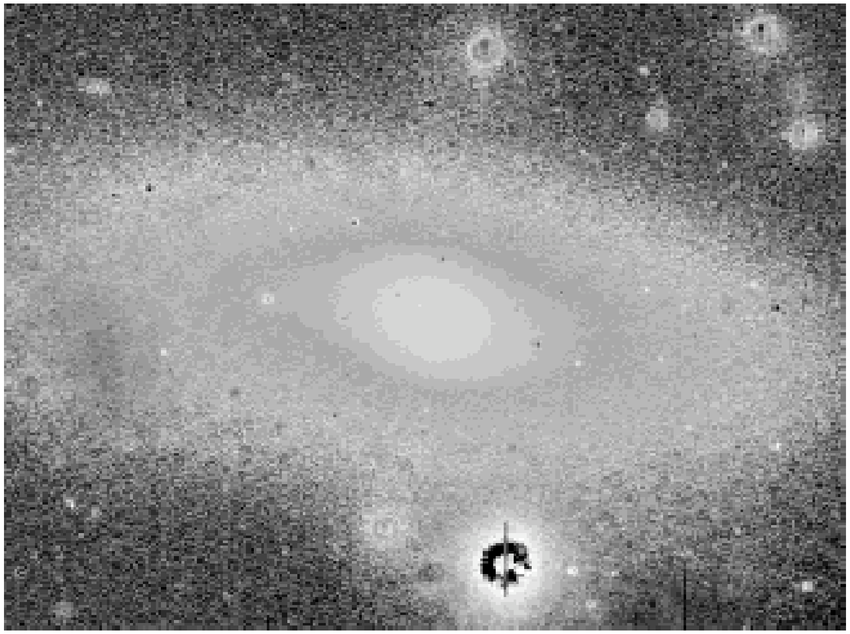
Constraints on disk formation

- NGC 1023 and NGC 3384 are barred
- NGC 3115 (no fuzzies) is not
- NGC 1023 α_B ~3.5 kpc

  FF ring ~ 4 kpc

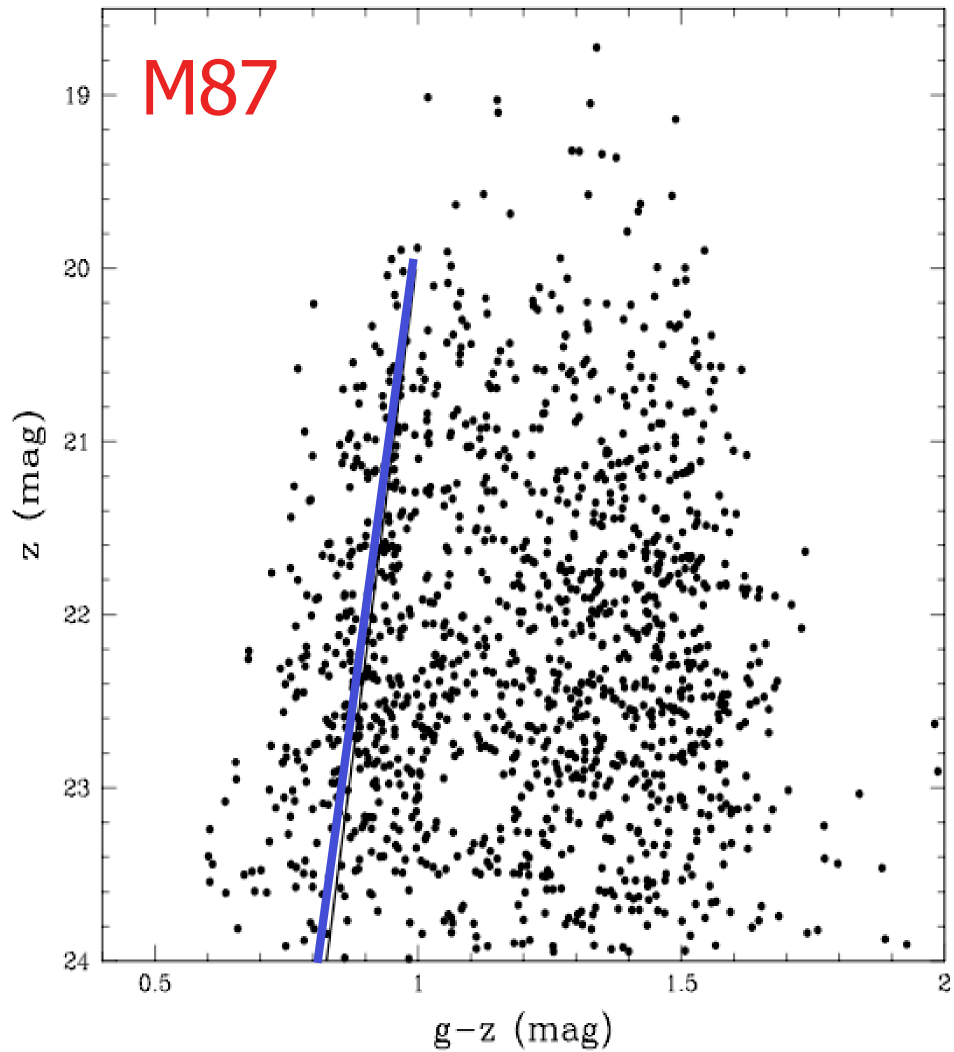
  (Debattista et al 2002)
- If FF formation is bar driven ⇒ disks/bars were present at z > 2

NGC 1023 B–I



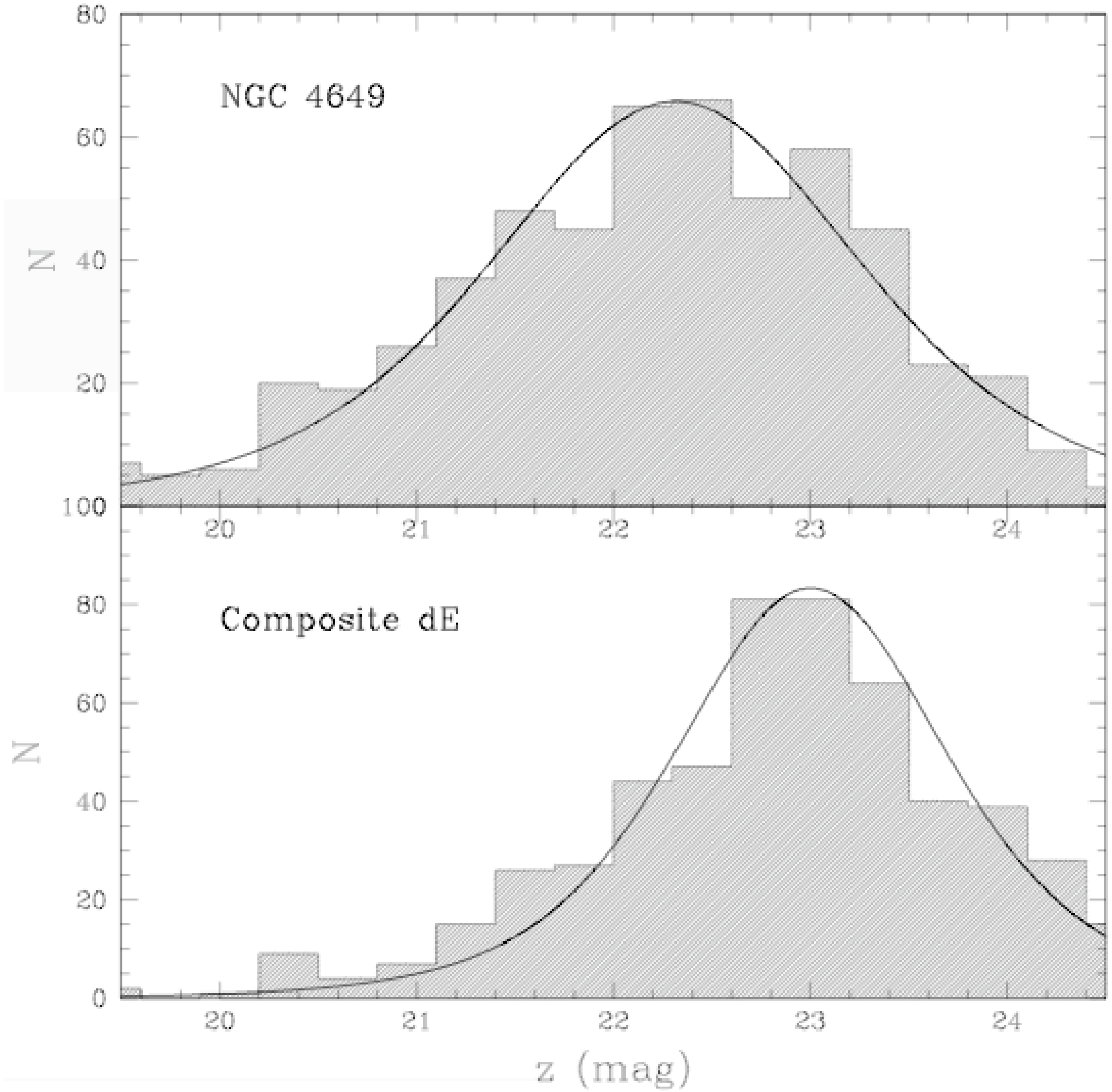
Surprises from ACS data

- Metallicity–mass relation for blue GCs
- Self enrichment?
- Blue GCs formed with DM halos?
- Very luminous (z>20) GCs are larger
- May be remnants of stripped dwarf galaxies
- "Cosmic H" common
- Metallicity spread
  red GCs ~0.7 dex
  blue GCs ~0.4 dex



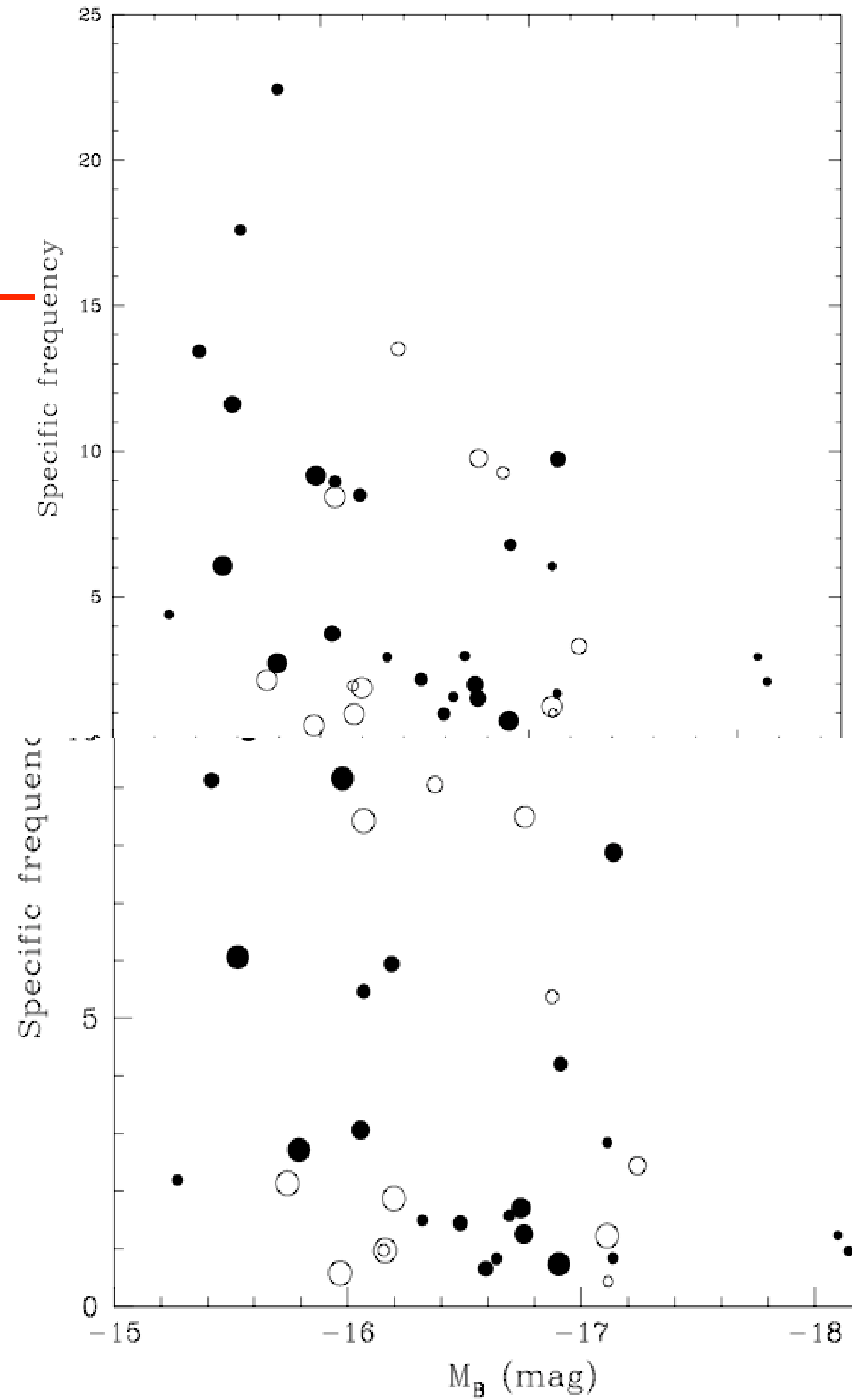
Dwarf Galaxies

- GCLF peak is fainter in dwarf galaxies by ~0.6 mag in z
- Difference in turnover mass
- Primordial or resulting from GC destruction e.g. forming dE nuclei?
- Dominated by blue GCs but many dEs bimodal with signficant red pops
- Mean blue and red GC colors consistent with extraplotation from luminous Es



Specific Frequencies

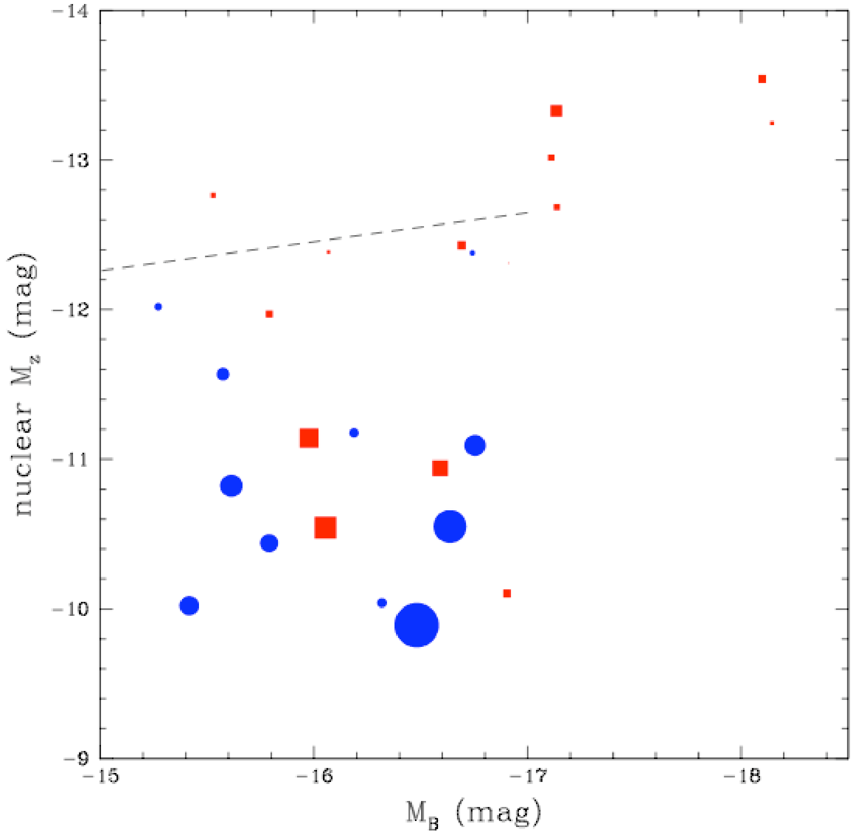
- No (inverse) correlation between S_N and L for dwarfs
- Large scatter in S_N with evidence for bimodality
- No connection with presence of nucleus or fraction of red GCs



Multiple formation channels for dEs

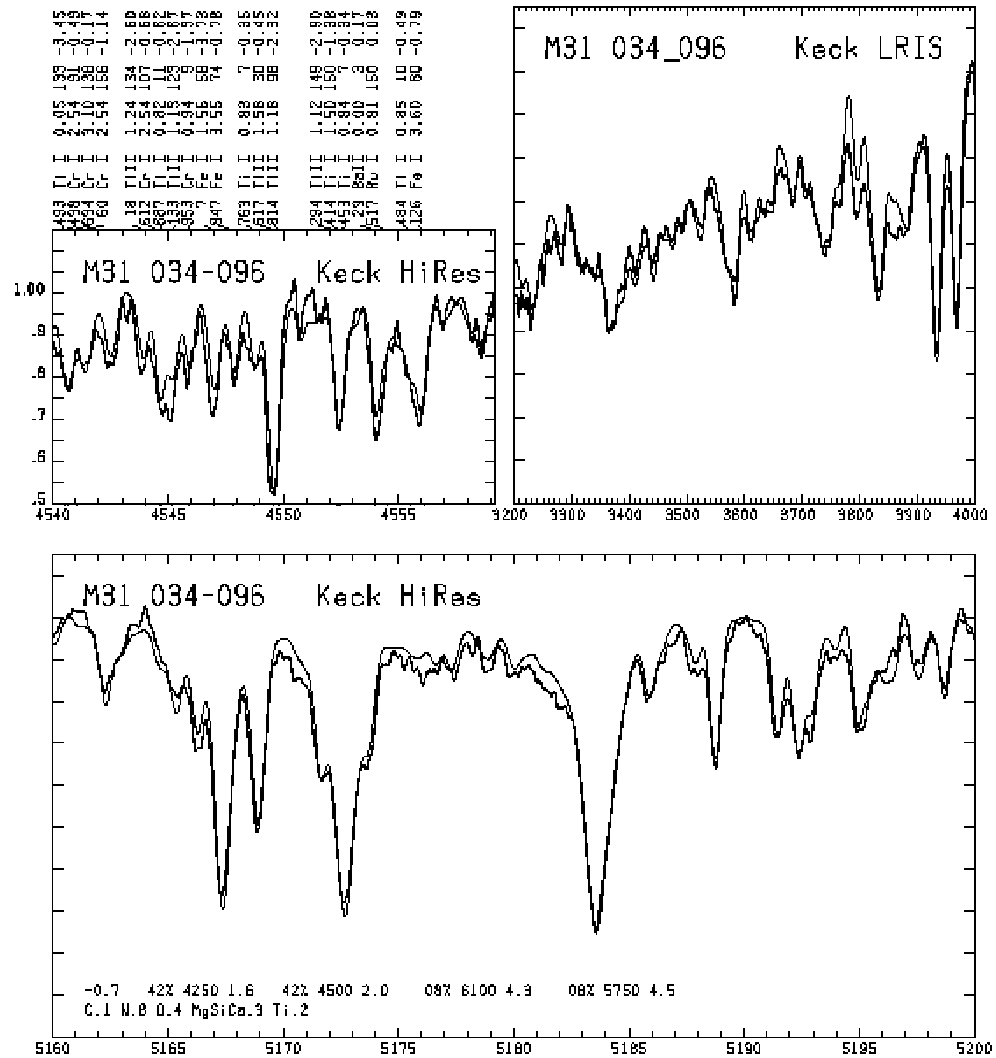
Evidence for 2 classes of dE nuclei

- Small bright red nuclei
  - Consistent with formation by dynamical friction
- Larger faint blue nuclei
  - Formed by dissipative process unconnected to GCs



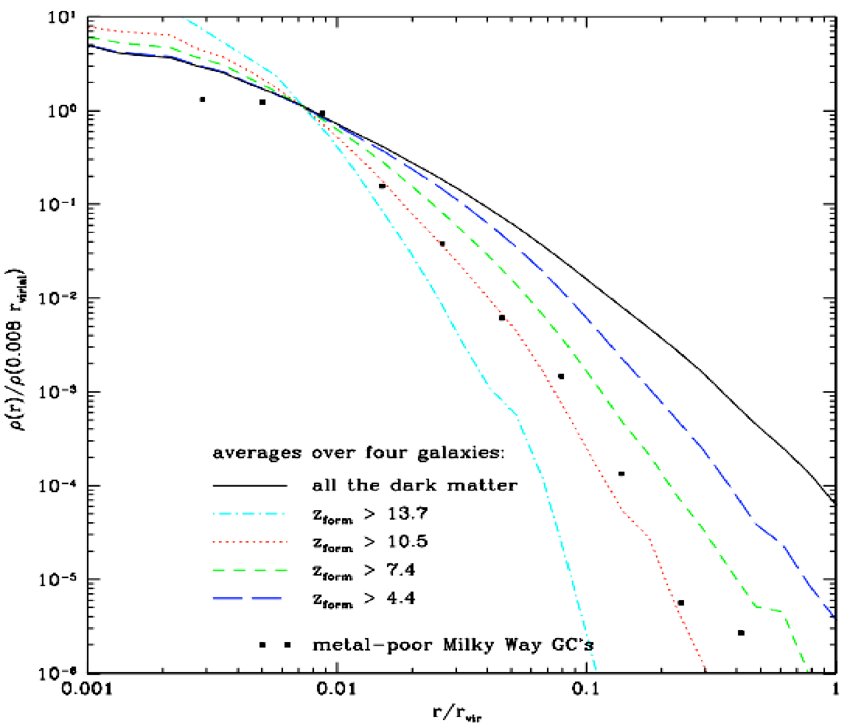
New Ways Forward

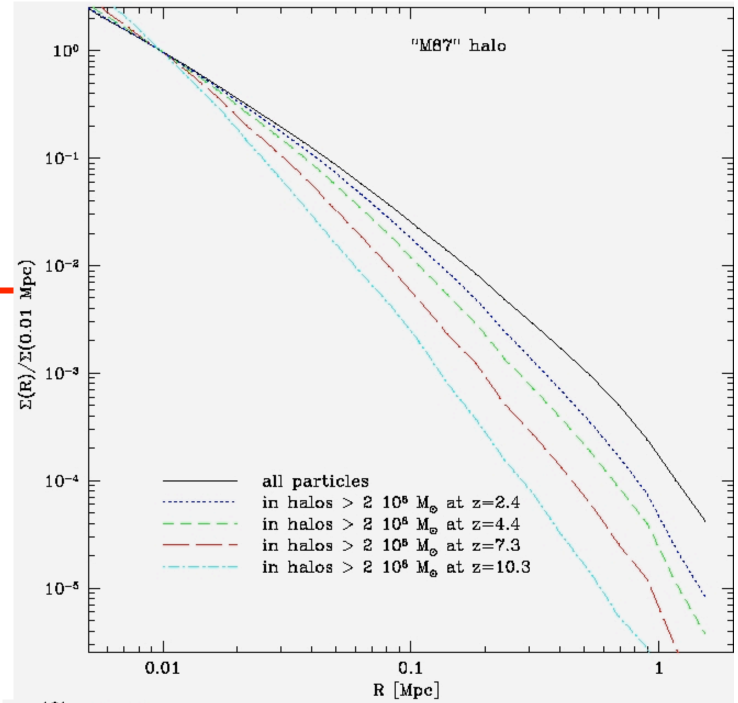
- HIRES spectroscopy and full-spectrum modeling for detailed element abundances → star formation histories and timescales for enrichment
- Wide field imaging programs

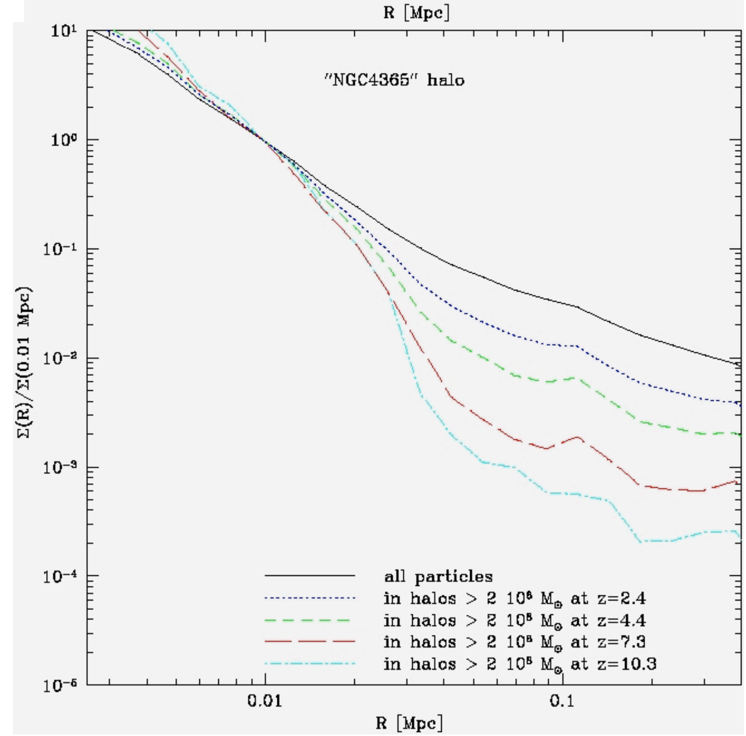


Wide field Imaging

- Epoch and (in)homogeneity of reionization
  GC surface density distributions
  for galaxies of different masses
  and environments







More Wide Field Imaging

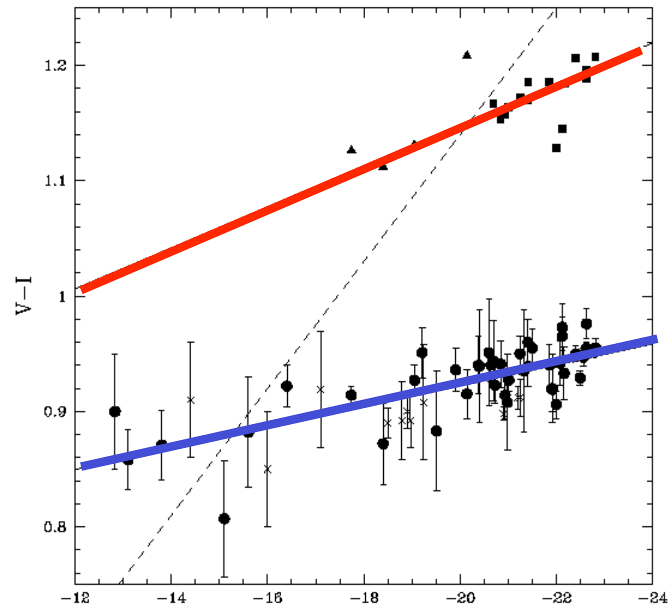
- Epoch and modes of galaxy assembly

Correlations of colors of blue (MP) and red (MR) GCs with host galaxy mass
  - for field galaxies: different merger histories, later formation
  - for spiral galaxies: do they lie low?
  - robust statistics for dwarf galaxies
  - intragalactic globular clusters

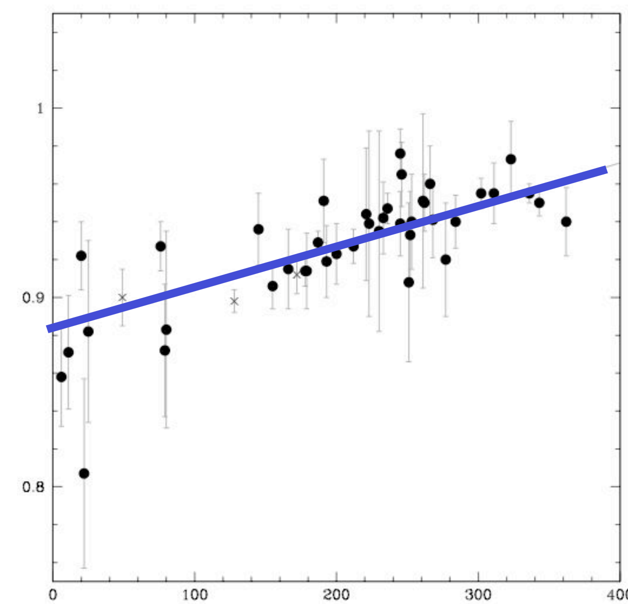
Correlations of GC numbers (per unit galaxy light) with host galaxy mass
  - specific frequency of blue GCs increases with host galaxy mass (Rhode et al 2005)

Relative numbers of reds and blues

Intermediate color peaks?



M_V



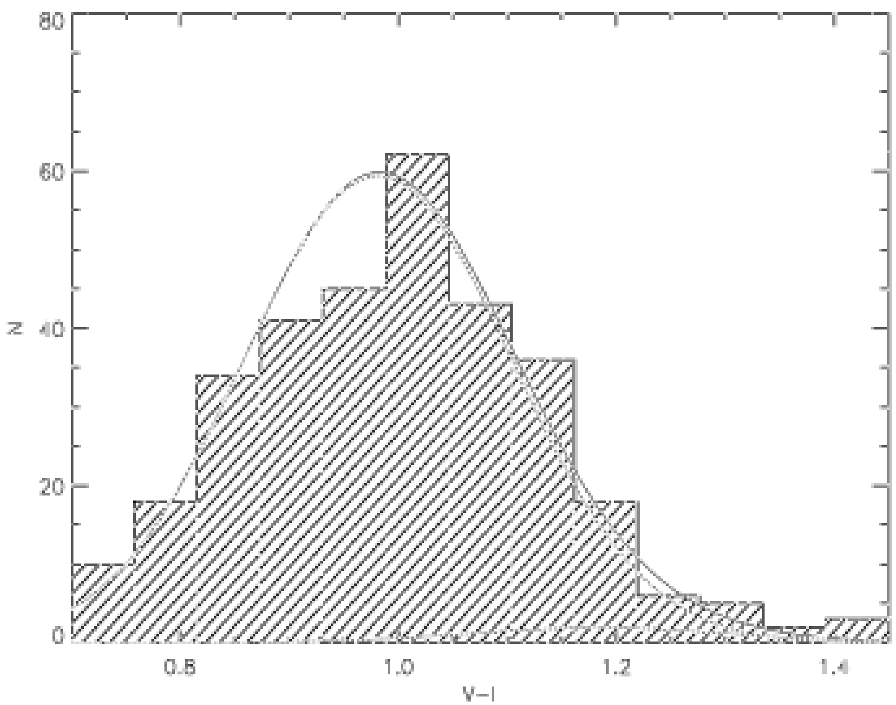
σ km/s

Summary

- GCs are the one of the best observable links between baryons and dark matter
- Constrain the epoch and modes of galaxy assembly
- The GC systems of early and late type galaxies are quite similar $\Rightarrow$ universal formation mechanism
- dE GCLF significantly different from luminous galaxies
- 2 formation channels for dEs implied by L, color, S_N, size relations
- Blue GCs trace the epoch and (in)homegeneity of reionization
- Blue GCs trace DM halos at earliest times, possibly the cosmic web
- Red GCs trace the build up of bulges
- Star formation in the massive bulges of early and late type galaxies was largely completed by z=2 or earlier, some disks were already in place at this epoch

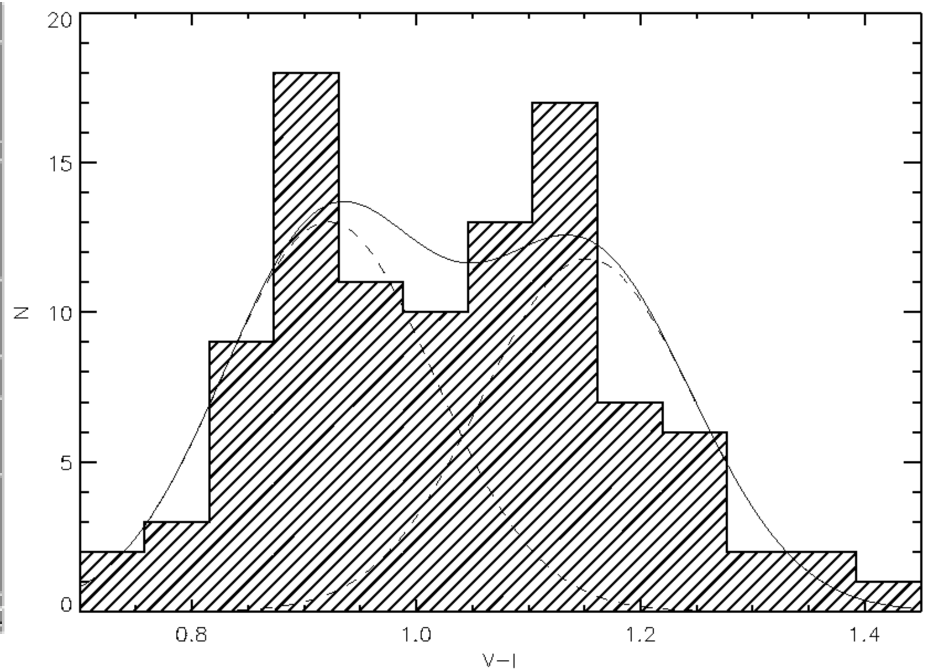
Unimodal Color Distributions?

NGC 4365



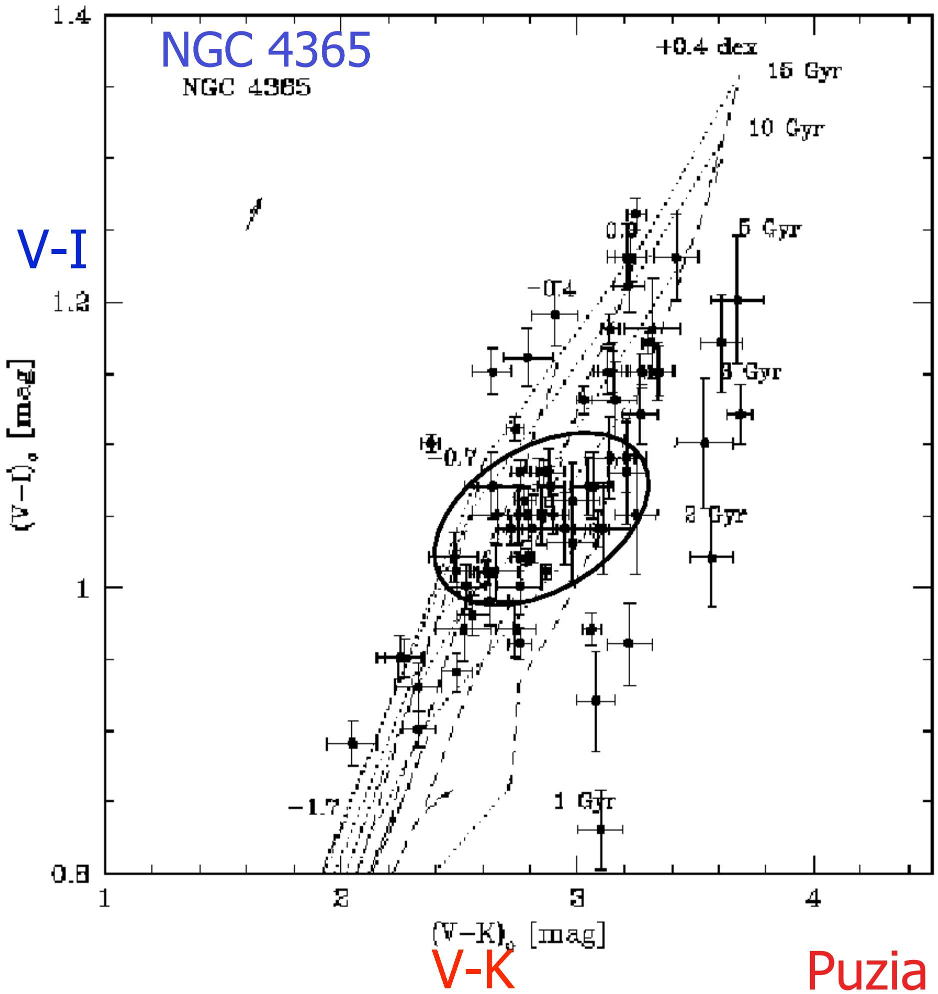
V-I

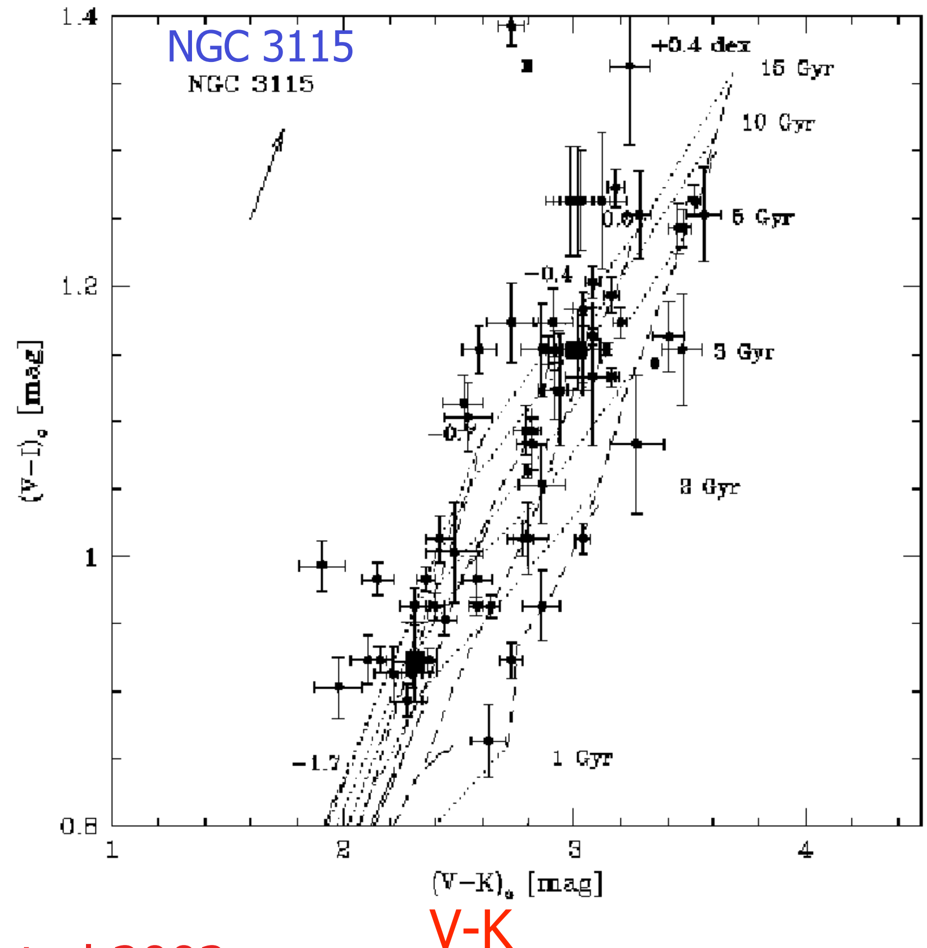
NGC 3115



V-I

Infrared Distributions





Puzia et al 2002

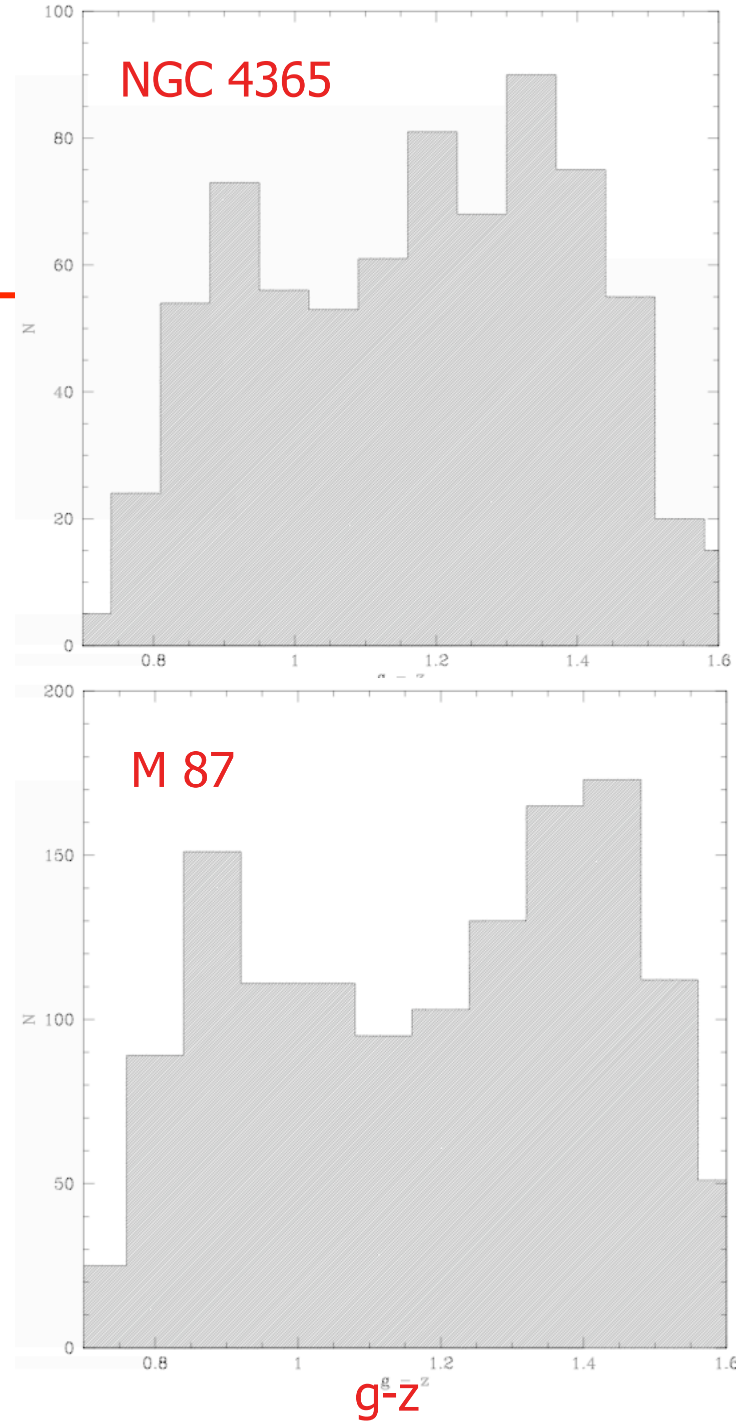
Where are the field stars?

- No signatures of recent mergers
- Luminosity-weighted age of ~ 14 Gyr for stellar population (Davies et al 2001)
- At most 1–5% of mass could be hidden in a 2–5 Gyr field star population
- Estimate (from Puzia et al IR data) ~ 25% GCs in inner regions are of intermediate age
- Where is the intermediate age stellar component?

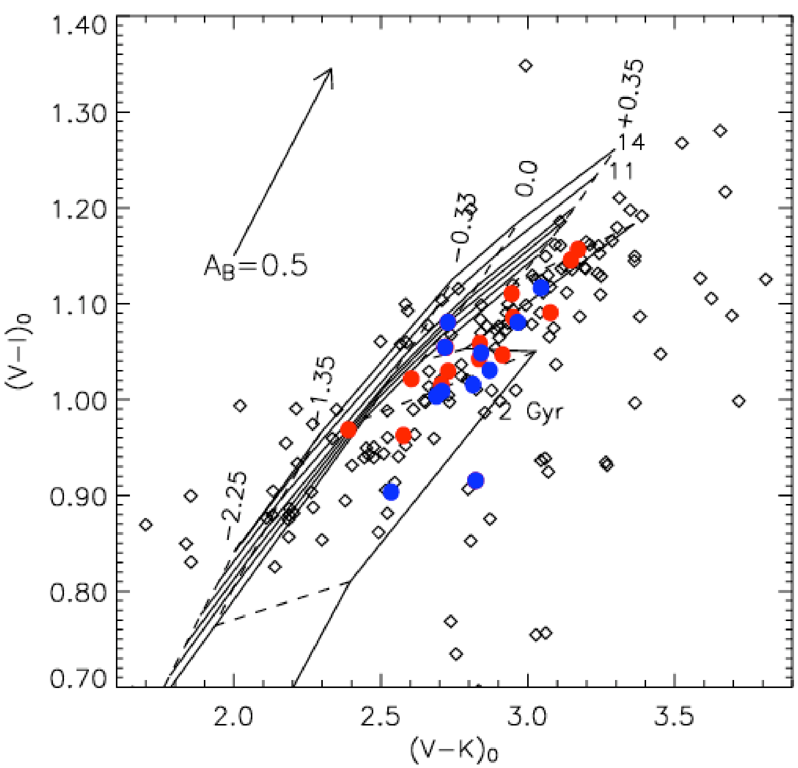
Trimodal Color Distribution

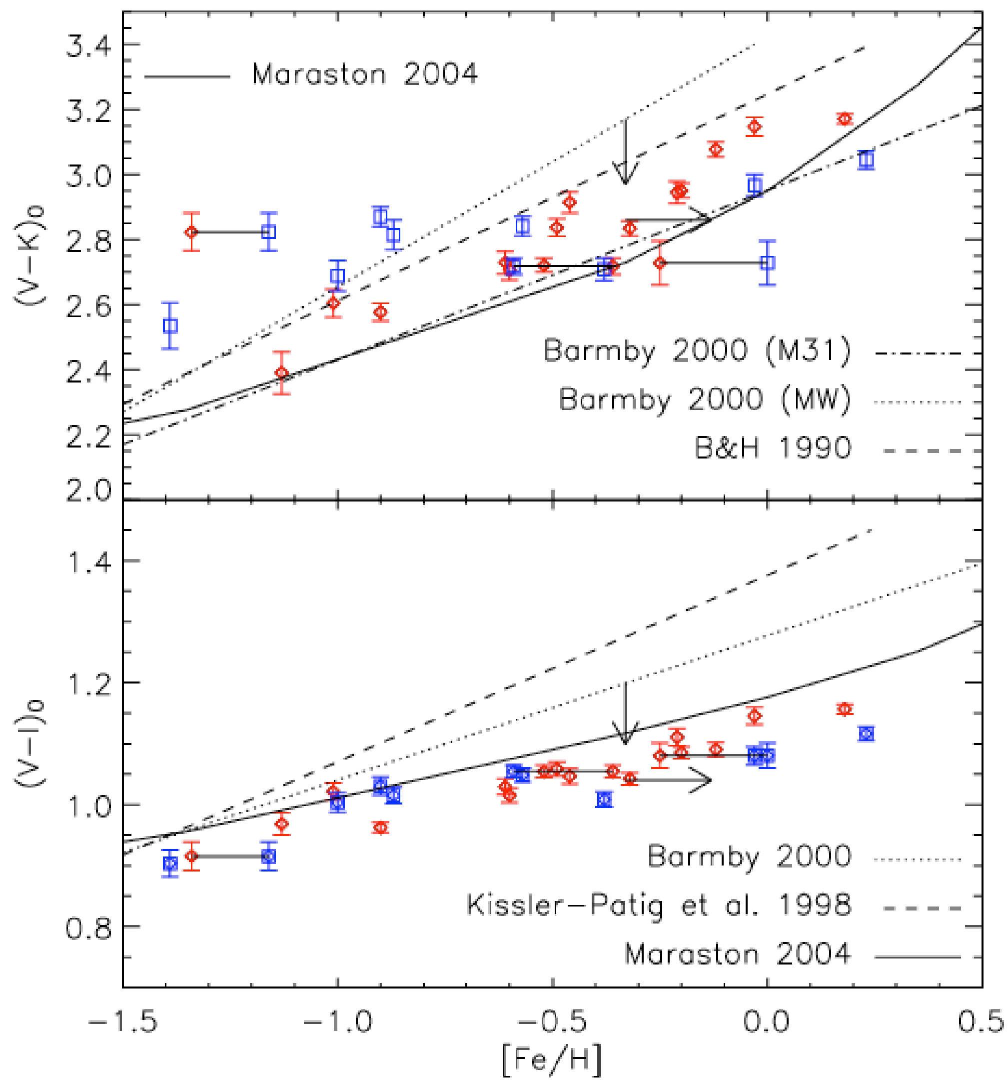
- 3 sub-populations:
  blue, "orange" and red
- All old, separated by metallicity
- Old mystery replaced by a new one
- Why was the star formation history of this galaxy so unusual?

Or was it?

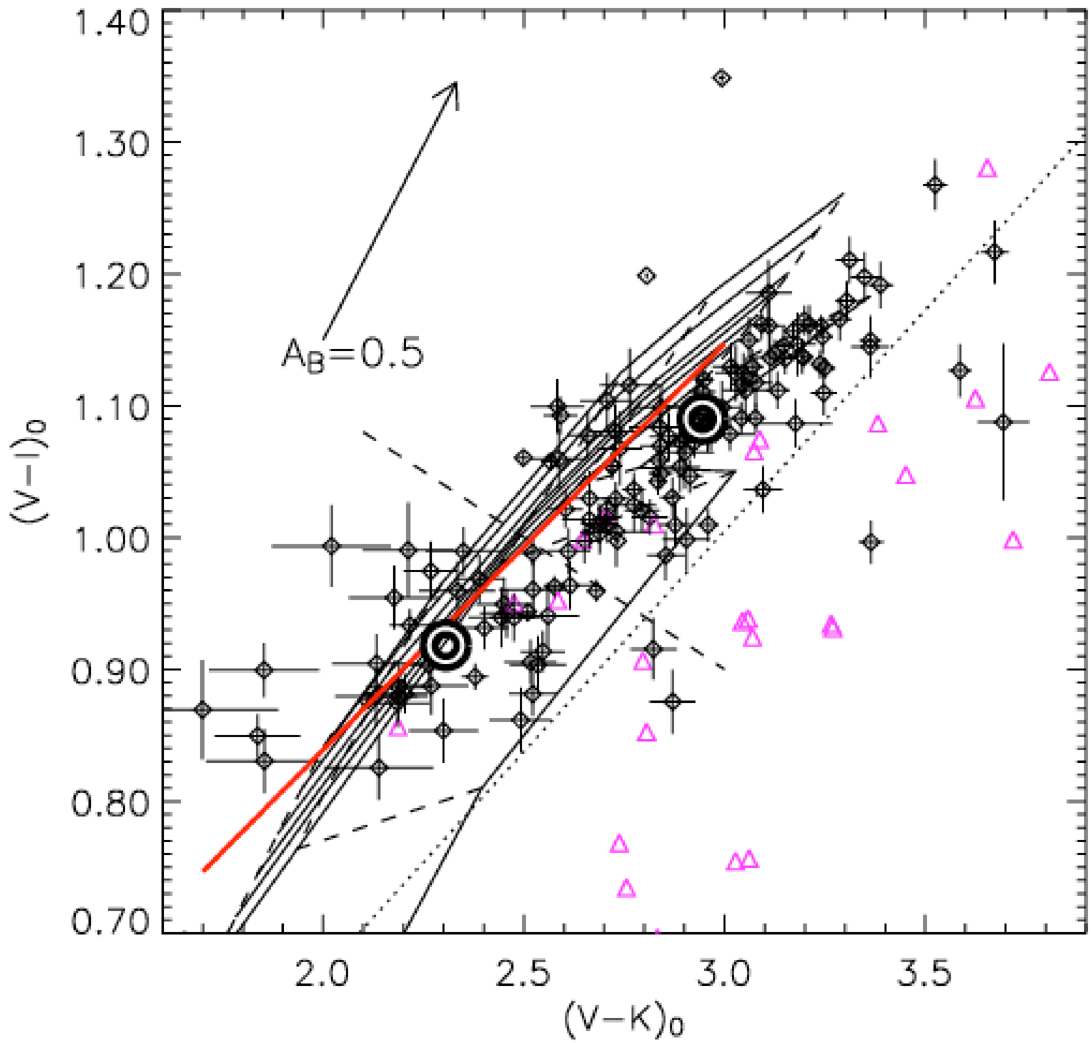


MODELS TOO BLUE





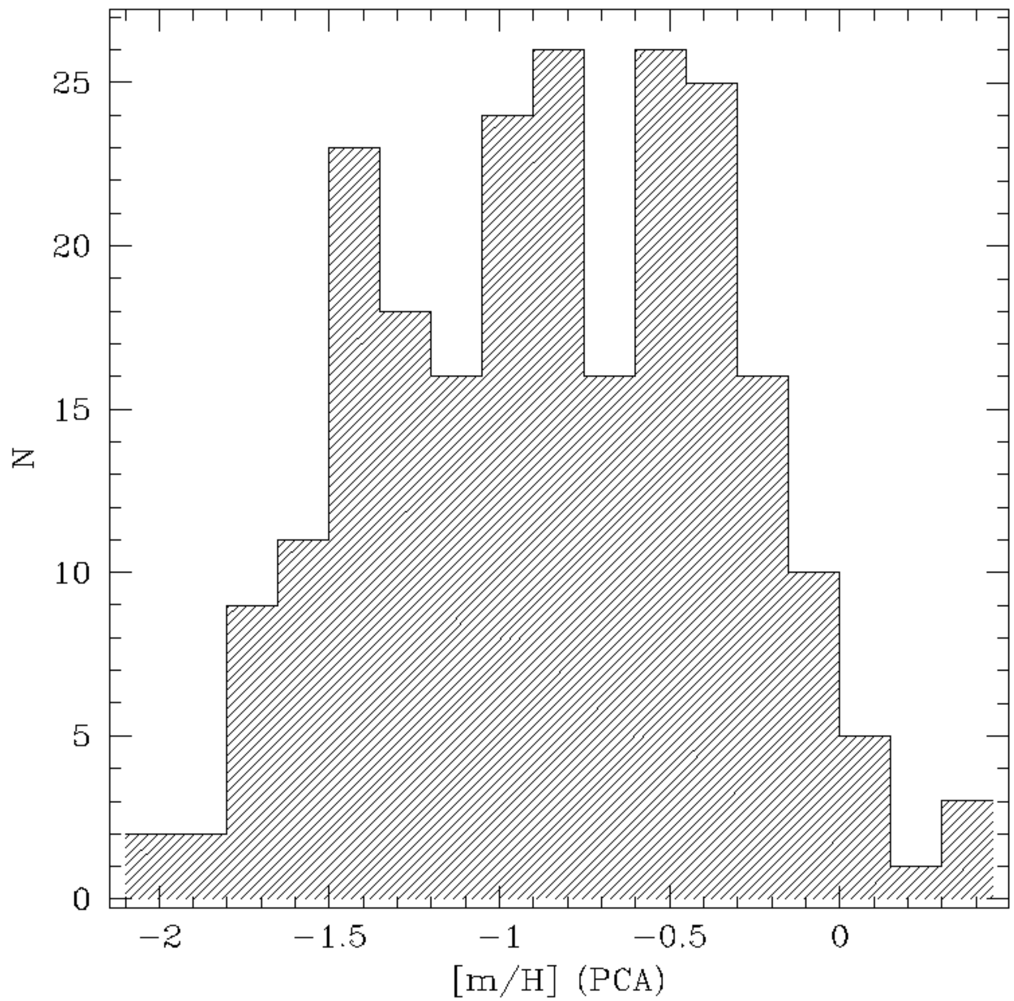
NGC 4365



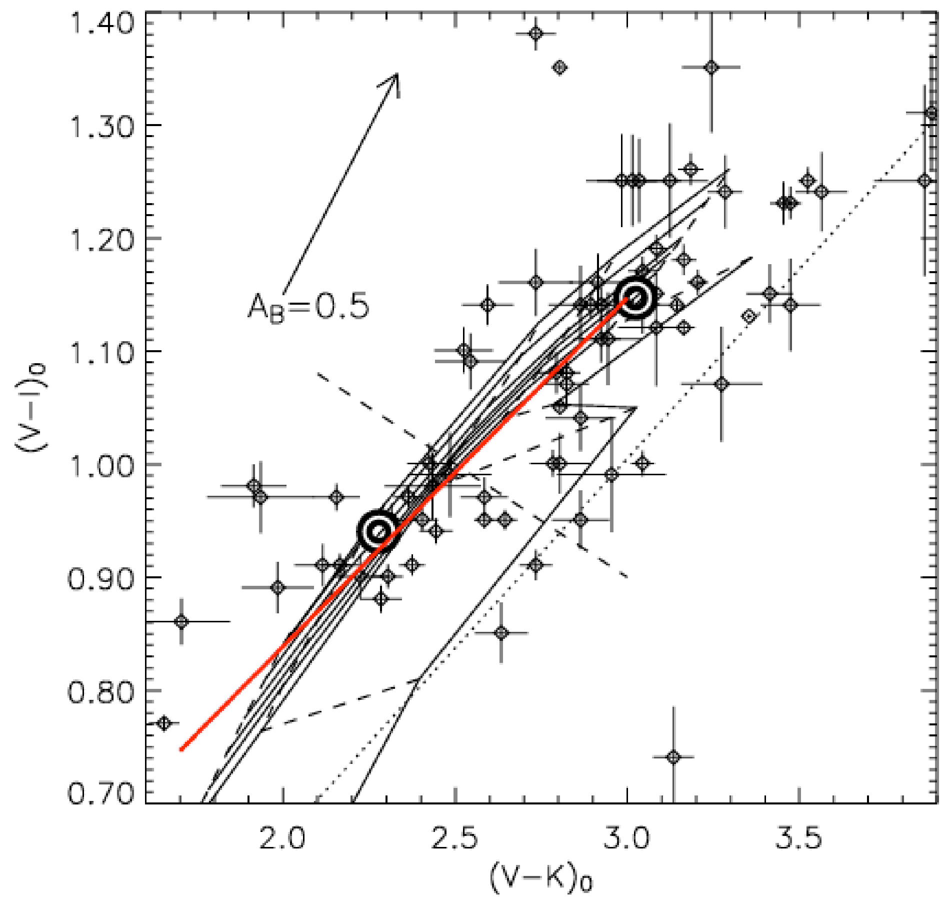
NGC 5128

- Old, intermediate metallicity peak
- ~20 out of 141 GCs with 2df spectra are young (< 8 Gyr)
- All – 0.7<[Fe/H]<0
- Sample selection ⇒ <<14%

Beasley et al in prep



NGC 3115



Summary & Implications

Color distributions of GCs in "nearby" galaxies

- Two (+) color peaks almost always preferred, consistent even for spirals
  Multiple epochs/mechanisms of formation universal

Age constraints from spectroscopy (best achievable with current technology)

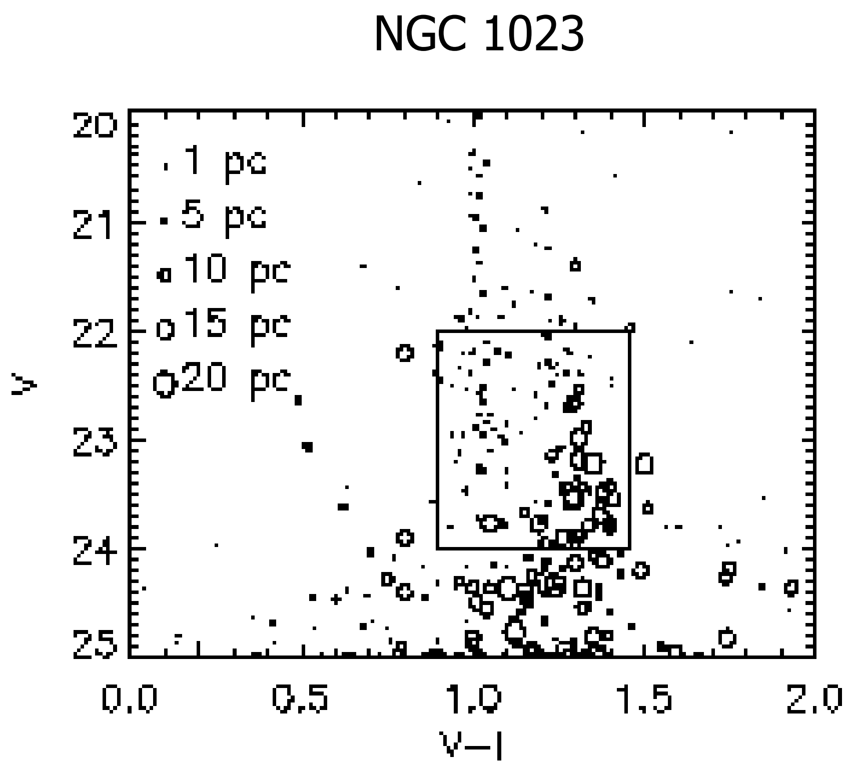
- Old ages of both sub-populations
  Inconsistent with major merger picture
  Galaxy assembly happened at high z (>2) – rest is just "frosting"

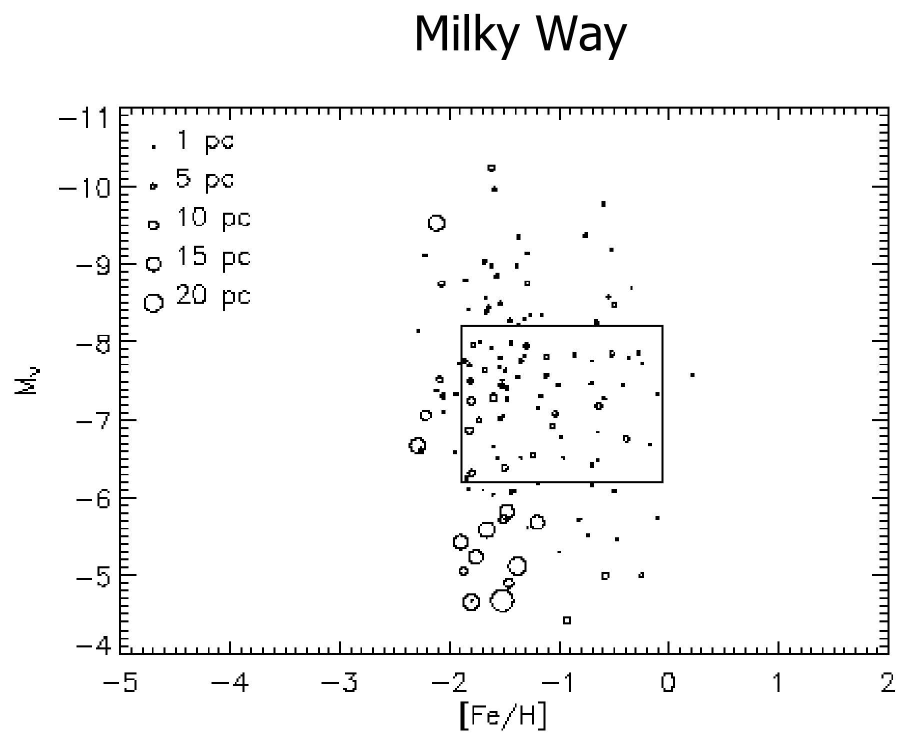
Correlations with parent galaxy properties

- Correlation between globular cluster colors and host galaxy luminosity (mass) and color for *both* reds *and* blues
  Blue relation difficult to explain under merger/accretion scenarios
  Both populations "knew" about the size of the final galaxy
  to which they would belong
  – Blue GCs formed first in DM halos "sitting" on high density peaks
  – Reached higher metallicities before formation was truncated
  – GC radial surface density distributions potentially constrain epoch and homogeneity of reionization

New Kind of Cluster

Globular Clusters





Open clusters are smaller, younger and less massive

No MW objects correspond in metallicity, luminosity and size

Color-Magnitude Diagrams

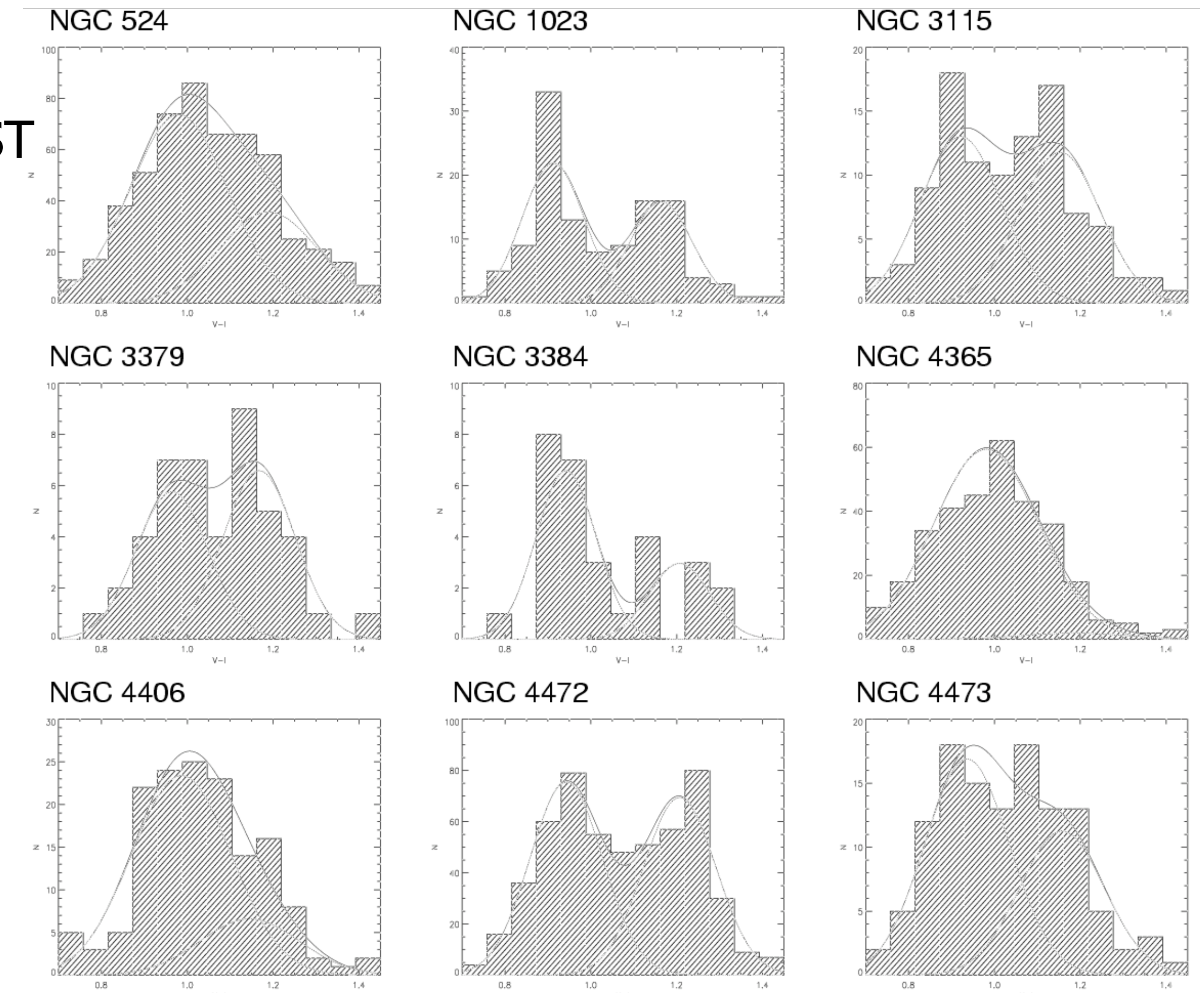
- 17 “nearby” early-type galaxies observed with HST
- Homogeneous deep dataset
- Data reach well below GCLF turnover

(Is GCLF really universal?)

- Average blue peak color $(V\text{–}I)_o = 0.95 \pm 0.02$
- Average red peak color $(V\text{–}I)_o = 1.18 \pm 0.04$

[Fe/H]= – 1.4, –0.6

(Kissler-Patig, Brodie, et al 1998)



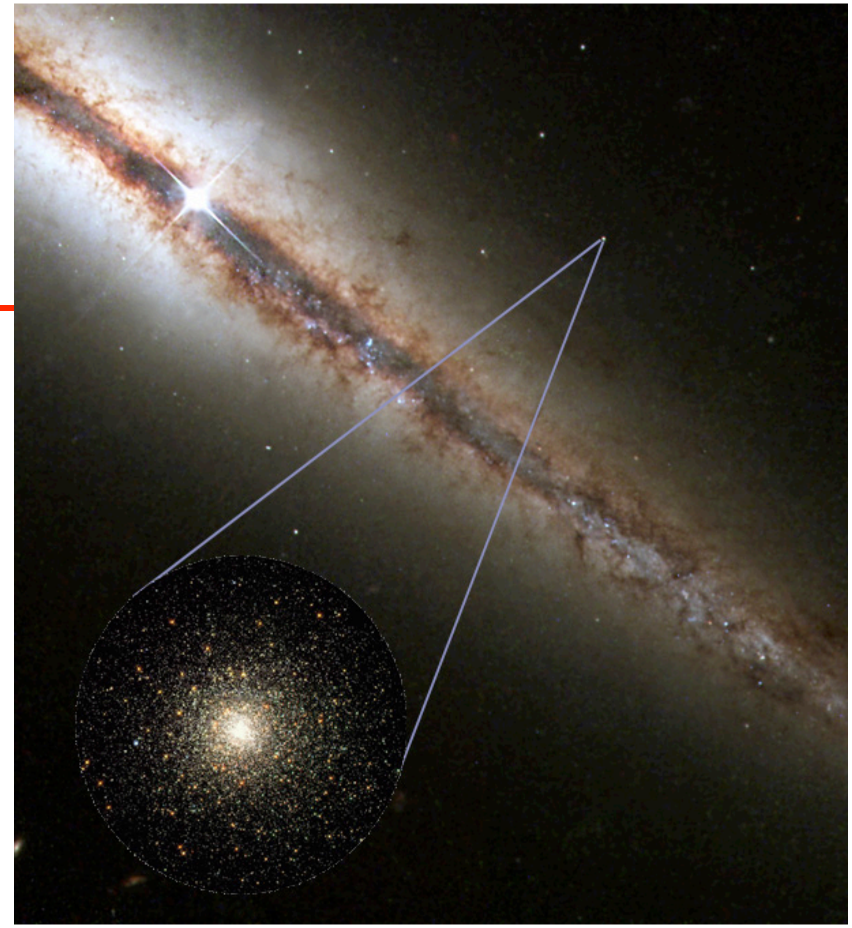
Larsen, Brodie, Huchra, et al (2001)

Bulge S_N

	M104	M31	MW
Hubble type	Sa	Sb	Sbc
Metal-rich GCs	667	100	53
Bulge-to-total	0.80	0.25	0.19
Disk S_N	4.2	0.21	0.19
Bulge S_N	1.1	0.63	0.84

The metal-rich GCs in M104 associated with bulge not disk component.

Numbers/Specific Frequency



- Metal-rich GCs in spirals are associated with bulge not disk
- # bulge (red/MR) GCs scales with bulge luminosity
- # red GCs/unit bulge light = bulge S_N ~1
- The total S_N for field ellipticals is 1–3 (Harris 1991)
- The fraction of red GCs in ellipticals is about 0.5
- The bulge S_N for field ellipticals is ~1
- Spirals and field ellipticals have a similar number of metal-rich GCs per unit (bulge) starlight

Constraints on Secular Evolution

- Number of metal-rich GCs scales with the bulge luminosity
- Metal-rich GCs are old
- Argues against secular evolution

Summary & Implications I

Color distributions of GCs in "nearby" galaxies

- Two Gaussians almost always preferred over a single Gaussian – peaks always consistent

  Multiple epochs/mechanisms of formation universal
- Similarities between peak colors in spirals and ellipticals
  Hints at universal GC formation processes

Results from spectroscopy

- Trimodal distribution(s) discovered for first time – rare?

  All 3 subpops are old, separated by metallicity
- Old ages of both sub-populations
  Inconsistent with major (late) merger picture
  Galaxy assembly happened at high z – rest is just "frosting"
- M31 has multiple age/metallicity populations
  Complex formation/recent accretion history

Summary & Implications II

Correlations with parent galaxy properties

- Slope of red GC color vs. galaxy mass relation same as galaxy color vs. galaxy mass relation
  Common chemical enrichment history for metal-rich GCs (in spirals and ellipticals) and the host
- Number of metal-rich GCs scales with the bulge luminosity + metal-rich GCs are old
  Argues against secular evolution
- Correlation between globular cluster colors and host galaxy luminosity (mass) and color for *both* reds *and* blues
  Difficult to explain under merger/accretion scenarios
  Both populations "knew" about the size of the final galaxy to which they would belong
  – fragments in which GCs formed at early times were already embedded in dark halos of final galaxy
  – one of few observational constraints on properties of pre-galactic clouds that combined to build the galaxies we see today

Conclusions

Our data are best explained by a formation scenario in which the bulk of both globular cluster sub-populations formed at early epochs within the potential well of the protogalaxy in multiple episodes of star formation